

(Cover) At the heart of the hypercube, which promises to be one of the most powerful computer systems in the world, is the hyperswitch integrated circuit. The hyperswitch, shown on the cover, will pass data at 400 megabits per second between individual nodes of the hypercube without interrupting the computation process. The hyperswitch was invented and developed at JPL in 1987 and is one of many technological advances that took place this year, a year filled not only with preparation for NASA's return to flight, but also with exciting developments across a broad spectrum of other fields.

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A description of work accomplished under a contract between the California Institute of Technology and the National Aeronautics and Space Administration for the period January 1 through December 31, 1987.

JET PROPULSION LABORATORY
California Institute of Technology
Pasadena, California

INTRODUCTION

■ The Jet Propulsion Laboratory of the California Institute of Technology is a federally funded research and development center that operates under contract to the National Aeronautics and Space Administration. The people of JPL share a common objective: research and development in the national interest.

Three institutional characteristics shape JPL's philosophy, mission, and goals: (1) as part of Caltech, JPL seeks the highest standards of scientific and engineering achievement, with excellence, objectivity, and integrity as guiding principles; (2) as NASA's lead center for unmanned exploration of the solar system, JPL has led the United States in lunar and planetary missions since the space age began, and performs other research, development, and space flight activities for NASA and other agencies; and (3) as a federally funded research and development center, JPL helps the United States solve technological problems.

Our primary mission evolved from pioneering rocket research through guided-missile work to space projects. Today JPL is a pre-eminent national laboratory with a budget of \$892 million and a work force of 5,465 people.

The Laboratory built and launched the first U.S. space satellite, Explorer 1. JPL's flight projects have included the Rangers and Sur-

veyors, pathfinders for the Apollo manned Moon landings; the Mariners to Mercury, Venus, and Mars; the Vikings to the surface of Mars; and the Voyagers to Jupiter, Saturn, and Uranus.

When national policy dictated that the United States should be self-sufficient in energy, JPL responded with research and development in solar photovoltaics, solar thermal energy, and electric vehicles. The Laboratory is answering today's emphasis on new defense efforts in a number of fields described in this report.

The year reported here, 1987, was a period of progress to help NASA recover from the accident of the space shuttle Challenger and to move forward with the space program. It was also a year of great strides in many fields of technology, including new computer architecture, robotics and automation, machine intelligence, and astrophysics.

And yet the Laboratory's major role continues to be exploration of the solar system, including planet Earth. For example, JPL's work helped scientists worldwide to understand the hole that has appeared in Earth's ozone layer. The Laboratory is conducting programs in Earth sciences and is exploiting technology to expand observations of the oceans and climate from space.

DIRECTOR'S MESSAGE

□ Twenty-five years ago, JPL accomplished the first-ever flyby of another planet with Mariner 2 at Venus. Ten years ago, we celebrated the launches of the twin Voyager spacecraft. Although their design life was only four years, the Voyagers produced tremendous scientific discoveries over a full decade, at Jupiter, Saturn, and Uranus. The Voyager 2 encounter with Neptune on August 24, 1989, will mark the end of the first, exciting, reconnaissance phase of planetary exploration. At that point we will have visited all but one of the planets and many of their satellites. JPL is proud to have had the major responsibility for that exploration.

NASA plans to resume shuttle flights in 1988. Galileo, Magellan, and Ulysses are scheduled for launch in 1989 and 1990. We worked hard this year to prepare the spacecraft for flight. Major technical challenges arose and, typically, JPL met the challenges. We look forward with great anticipation to the coming discoveries from those missions.

We continued our role as NASA's lead center for planetary exploration this year, proceeding with plans and development for the next phase of scientific inquiry. That phase focuses on two major objectives: detailed study of the origin and formation of the inner solar system, and investigation of objects beyond Mars for evidence of molecular evolution. We are developing the Observer and Mariner Mark II classes of spacecraft, respectively, for the journeys. In pursuit of the first goal, work continued on Mars Observer, scheduled for launch in 1992. Mars Observer will study the surface and atmosphere of Mars and provide data for future Mars missions, for sample return, or manned exploration. Focusing on the second objective, JPL further developed plans for the Comet Rendezvous Asteroid Flyby and Cassini missions, both of which could start in 1990. Those complementary missions would investigate a comet and an asteroid, and Saturn and its satellite Titan, for evidence of the emergence of organic

material, the building block of life, within the solar system.

Deepening our understanding of the solar system also helps us better understand our own planet, Earth. In accord with NASA recommendations, JPL strengthened its capabilities for sensing atmospheric, oceanic, and geologic phenomena from space. Development proceeded on the NASA Scatterometer Project and TOPEX/Poseidon (an oceanographic altimetry mission managed by JPL) and other instruments for Earth observation. We also contributed to the critical study of the ozone layer over the Antarctic. The work will continue as we apply solar-system science and expertise to our home planet.

JPL performed critical roles this year in a range of joint activities. We led the Mars Rover Sample Return study with the Johnson Space Center. That effort will be expanded in 1988 and has far-reaching implications for future Mars missions, and possibly for expanded international cooperation.

To support NASA, JPL established the Space Station Support Office in Reston, Virginia. There JPL people are establishing the system requirements for the Space Station.

In addition, the Deep Space Network contributed to international cooperation with its preparations to track the Soviet spacecraft Phobos in 1989 and with its plans to array NASA's antennas and the Parkes antenna in Australia for Voyager 2's Neptune encounter.

Yet JPL is remarkable for the breadth of our investigations. Our advanced-technology development includes major new thrusts in infrared and submillimeter observations, automation and robotics, and space microelectronics. We are working on such innovative mission concepts as the Quicksat, a lightweight spacecraft that can be readied quickly with small rockets, the mission to one thousand astronomical units (TAU), and the Circumstellar Imaging Telescope (CIT) to study other planetary systems orbiting other stars.

Thus, somewhat paradoxically, in a time of suspended launch capabilities, we remain challenged and busy. In 1987, JPL performed almost \$1 billion worth of work for NASA and other sponsors. We continued several defense and civil projects that apply space-related capabilities to important national problems.

This year we reorganized in response to the evolving nature of technology, science, and instruments. We established two new offices: the Office of Space Science and Instruments and the Office of Technology and Applications Programs. Advanced mission studies were placed in the Office of Flight Projects. The changes will strengthen the Laboratory's ability to meet the demands of current and future missions.

Several distinguished members of the JPL management team retired this year, including Bob Parks and Fred Felberg. We miss their strengths. Talented replacements were appointed. Pete Lyman, who was Assistant Laboratory Director, is now Deputy Director. JPL will continue to earn its excellent reputation with outstanding achievements in space science and engineering.

As we look back over the year, three principles stand out, showing us what JPL is all about. First, as a part of both Caltech and NASA, we bring unique capabilities to space science and engineering. Our ties with the Caltech campus remain strong and vital, enriching the research and technology base that we offer. Second, our primary objective is, and continues to be, the exploration of the solar system. We are laying a strong foundation from which to continue that role when the shuttle launches resume. Third, by far our greatest asset is our people. With their creativity, determination, skill, and character, the Laboratory will continue to make major contributions to the understanding of Earth, the solar system, and beyond.



Dr. Lew Allen

Dr. Peter T. Lyman

Lew Allen
Director

FLIGHT PROJECTS

■ The Laboratory spent the year planning and preparing for the resumption of space shuttle flights. In some realms, our progress involved truly imaginative, creative thinking to incorporate new launch-vehicle configurations into existing mission plans. Meanwhile, as it has for 10 years now, Voyager 2 flew on. Its closest approach to Neptune is scheduled for August 24, 1989.

Laboratory teams also prepared for future projects. The Comet Rendezvous Asteroid Flyby mission to Comet Tempel 2 did not win new-start authorization for 1989; however, we have identified other comets and asteroids as candidate targets for a 1990 new start. Studies went forward on the Cassini mission to Saturn and its largest satellite, Titan.

We also began studies of a Mars Rover Sample Return mission with the Johnson Space Center. Scientists and engineers continued their studies of a mission to one thousand astronomical units, TAU, a concept for a 21st-century interstellar mission that would fly a spacecraft 1,000 times farther from the Sun than Earth is.

Exploration of planet Earth received a boost when Congress authorized the Ocean Topography Experiment, a joint U.S.-French oceanographic mission.

CURRENT MISSIONS

Voyager

Voyager scientists continued to analyze data from Jupiter, Saturn, and Uranus; took new cruise-science data from both spacecraft; and prepared for Voyager 2's August 1989 encounter with Neptune.

Because Neptune orbits about half again as far from the Sun as Uranus, sunlight will be only half of what it was at Uranus. That presents a challenge for the project to acquire scientific data in such dark surroundings. A similar challenge exists in then transmitting the data to Earth. Modifications to the spacecraft and the ground system are required to compensate for the great distances between the spacecraft, the Sun, and Earth.

Teams are modifying ground software and Voyager 2 flight software for longer exposure time on the cameras. A new technique of image-motion compensation will be used at Triton, Neptune's large satellite, to reduce image smear.

Improvements in the communication system will allow us to gather almost as much scientific data at Neptune as we gathered at Saturn and at Uranus. The 64-meter antennas of the Deep Space Network (DSN) have been enlarged to a 70-meter diameter. We will array the DSN antennas with antennas from other organizations, much as we did for Voyager at Uranus. The 64-meter Parkes radio-astronomy dish in Australia will be arrayed with the Canberra DSN stations. The twenty-seven 25-meter antennas of the Very Large Array at Socorro, New Mexico, will be arrayed with the Goldstone DSN antenna. Negotiations are under way with Japan to array its 64-meter Usuda antenna with the Australian stations for radio-science measurements.

The project is planning and developing computer programs for Voyager 2's command sequences for the Neptune encounter, which will last from June to September 1989.

Voyager 2 photographed Neptune and its satellite Triton on January 16, from a distance of more than 1.3 billion kilometers.



Computer scientists generated this series of scenes of Uranus' satellite Miranda from photographs taken by Voyager 2.

Galileo

The Galileo project to study Jupiter, its satellites, and its magnetic environment with an atmospheric probe and a 22-month orbital tour moved forward on several fronts.

After NASA cancelled the Centaur as an upper stage for the shuttle, the project had to find a way to get Galileo to Jupiter on the shuttle using a two-stage inertial upper stage (IUS). The IUS, however, lacks the energy for a direct flight to Jupiter. The solution, called VEEGA (for Venus–Earth–Earth Gravity Assist), is a six-year flight, passing Venus once and Earth twice to gain velocity. Galileo will fly by two asteroids—Gaspia and Ida—adding new opportunities for mission science.

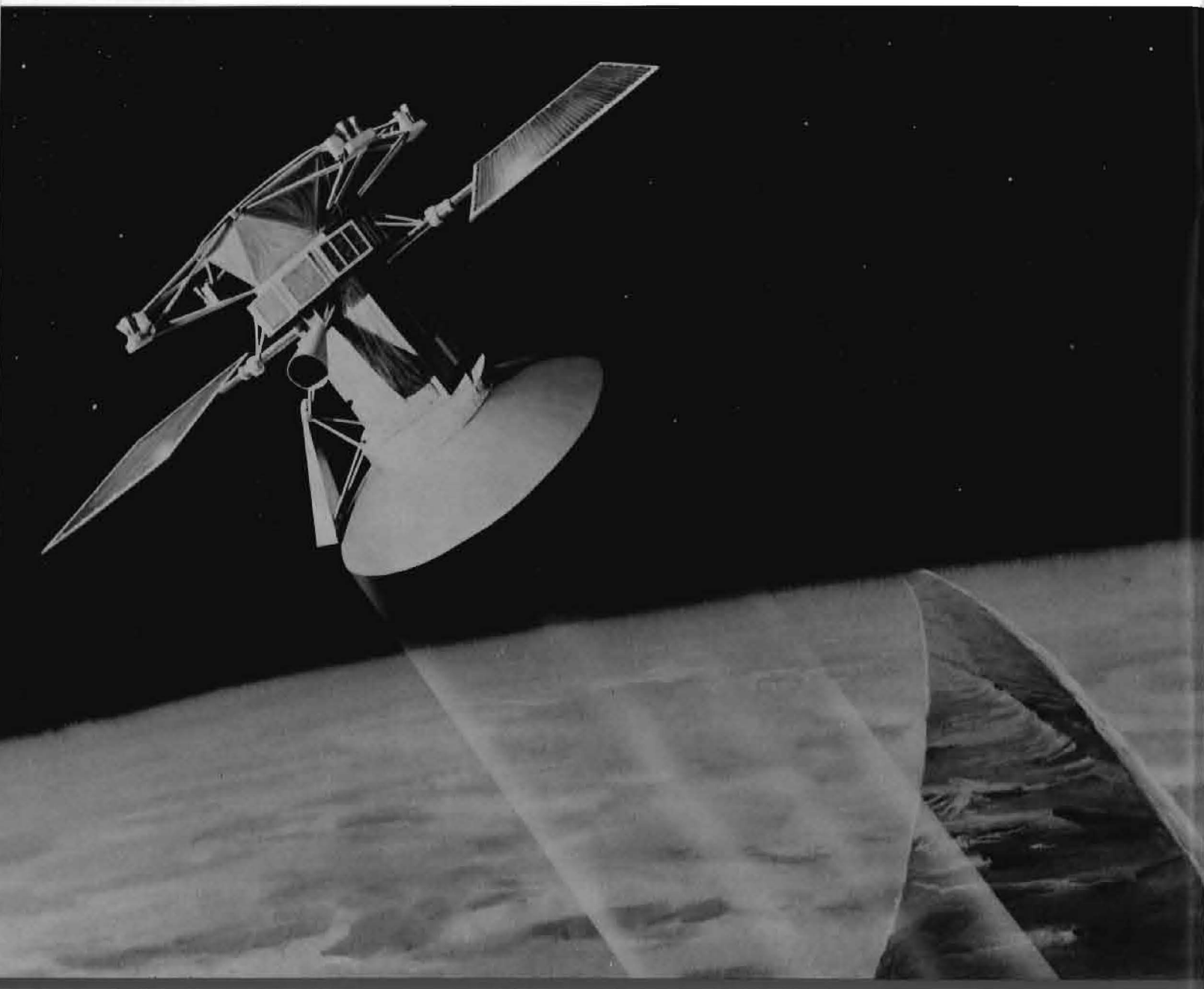
Close observation of the two asteroids and studies of Venus, Earth, the Moon, and interplanetary space will take place on the trip to Jupiter. New science will include a search for lightning storms and compositional variations in Venus' atmosphere, the first studies of the Moon's north pole, and a search for traces of comets in the inner solar system. The first close-up data on asteroids will include high-resolution images, studies of surface composition, thermal properties, mass, and rotation rates.

Three characteristics of the new mission configuration call for changes to existing flight hardware. Selection of a new upper stage required new hardware to join the upper stage to Galileo. The longer cruise to Jupiter meant we had to replace hardware that might not survive to the end of the mission. Adjustments are being made to Galileo's power source—the radioisotope thermoelectric generators—to compensate for declines in power.

The major redesign work on Galileo is required for its flight into the inner solar system to Venus, where sunlight is twice that at Earth and 50 times that at Jupiter. During the flight through the inner solar system the communication link to Earth runs in the opposite direction from that of a direct flight to Jupiter. A backward-looking antenna was added to cover the gap. Extensive changes in the thermal design, including new blankets and sunshields, have been completed. Late in the year, assembly of new hardware began at JPL's Spacecraft Assembly Facility.



Engineers concentrate on data from tests of new Galileo components required for the six-year flight through the solar system to Jupiter. The tests end successfully.



The Magellan spacecraft's imaging radar peers through the clouds of Venus to map the planet's unseen surface in this artist's rendering.

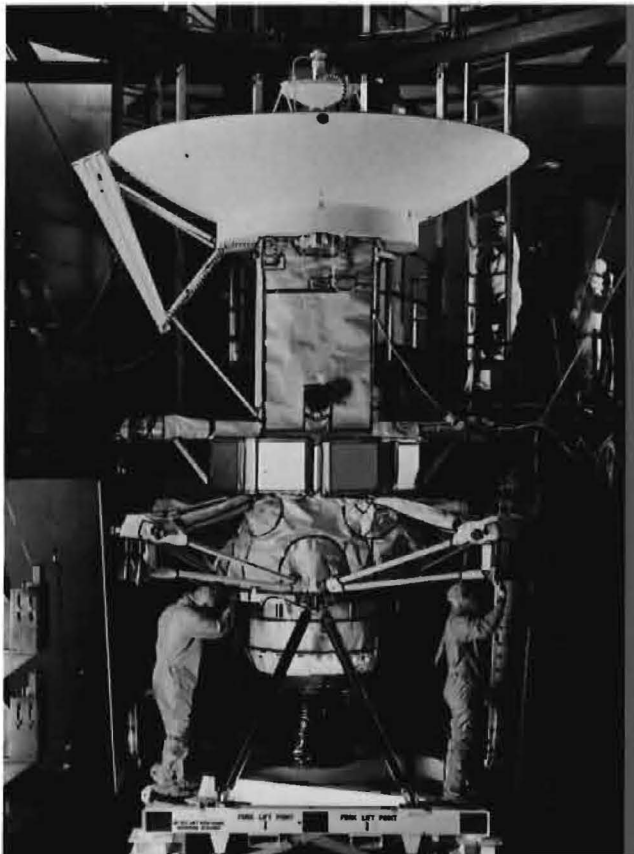
Magellan

Magellan's mission is to map the surface of Venus with sophisticated imaging radar. Magellan will be the first planetary spacecraft launched when shuttle flights resume.

Assembly testing of the spacecraft started in March at Martin Marietta in Denver. Hughes Aircraft in Culver City, California, delivered a version of the radar for integration and testing in summer. Delivery of flight radar is expected in spring 1988. Qualification of the spacecraft and radar will follow, and Magellan will be shipped to Kennedy Space Center in November 1988.

Once Magellan arrives at Venus, its radar will scan the surface from a nearly polar, 3.15-hour orbit as Venus rotates below. Because Venus rotates only once in 243 days, it will take that long to complete the mapping.

Magellan's images will show features as small as 150 meters across and will cover 70 percent of the surface. The spacecraft will take more imaging data than all previous planetary missions combined. It will use new multi-mission capabilities in JPL's Space Flight Operations Complex and Multimission Image Processing Laboratory.



Martin Marietta

Construction work on the Magellan spacecraft proceeds at the Martin Marietta plant in Denver, Colorado.

Ulysses

Ulysses, a mission to explore both poles of the Sun, will be launched to Jupiter in October 1990. Jupiter's gravity will hurl the spacecraft back toward the Sun's south pole. Thus, Ulysses will become the first spacecraft to fly so high out of the ecliptic plane.

The spacecraft was provided by the European Space Agency (ESA) and is now stored in Germany. The science instruments are at the principal investigators' facilities, and the nuclear power source is with the U.S. Department of Energy. Instruments and spacecraft will come together again in 1989 and final testing will begin.

The upper stage was changed from a Centaur to an inertial upper stage plus a payload-assist module. Project engineers at JPL carried out the design and engineering required to mate the upper stages to the space shuttle and Ulysses.

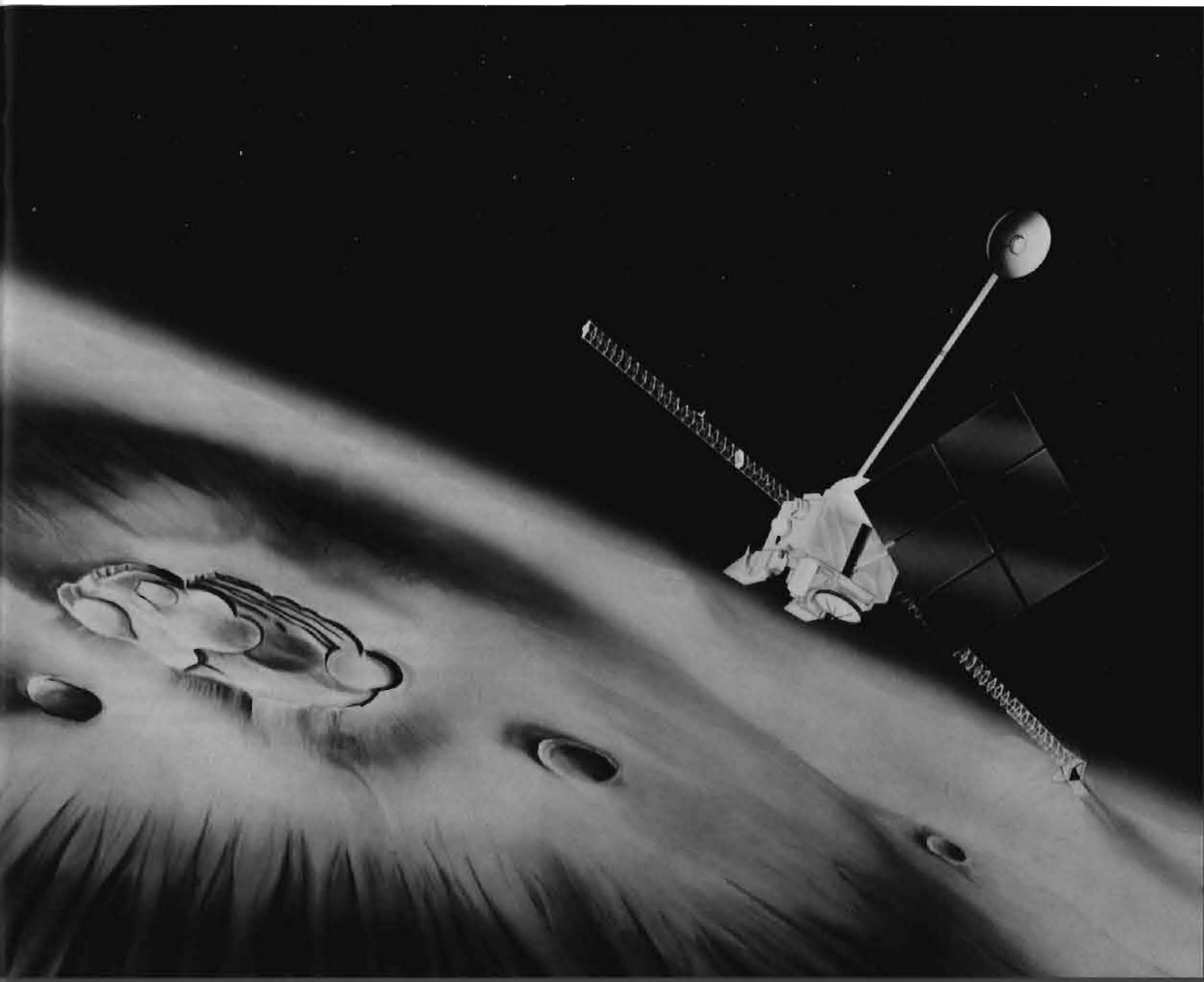
Mars Observer

Mars Observer was in early development toward a 1990 launch at the time of the Challenger accident. Because other planetary launches were rescheduled into that time frame, the Mars mission was delayed to a 1992 launch. Project leaders began revision of plans, schedules, and costs with contractors and scientists. The project has completed preliminary design and safety reviews.

Early in the year, NASA and JPL selected the Mars Observer scientific investigations. The mission will conduct new, planet-wide studies of geology and climate.

Mars Observer was also a part of discussions held between the United States and the Soviet Union under the provisions of a bilateral agreement, "Cooperation in the Exploration and Use of Outer Space for Peaceful Purposes," signed in April. Meetings in Moscow and Paris in December furthered the cooperative interests that involve Mars Observer, the Soviet Phobos mission, the DSN, and a 1994 Soviet Mars surface mission. Soviet scientists proposed that Mars Observer support a Soviet balloon-borne package as an additional communications relay to increase the data return. If it is technically feasible, we would like to incorporate the package into our mission.





The Mars Observer spacecraft orbits the red planet high above the great volcano Olympus Mons in this artist's rendering.

FUTURE MISSIONS

Comet Rendezvous Asteroid Flyby

The Comet Rendezvous Asteroid Flyby (CRAF) will fly by one or more asteroids and then will rendezvous and fly beside a short-period comet. The CRAF project worked on mission and science development with the assumption that project start would be included in NASA's budget for fiscal year 1989.

NASA selected a payload of 13 instruments. Perhaps the most innovative is a surface penetrator, which carries five sensors. The spacecraft will fire the penetrator into the comet, and the sensor will take the first in situ measurements. The University of Arizona tested the penetrator and found that the device could penetrate hard sea ice at shallow angles. Development proceeded on the science payload and on other subsystems through the year.

The Federal Republic of Germany plans to supply a large spacecraft-propulsion module, on which maneuvers and attitude-control depend, and an instrument to measure dust escaping from the comet. The German team has completed its propulsion system studies.

The project did not receive Congressional approval for the anticipated fiscal year 1989 new start. Engineering studies and progress are transferable, though, and Comets Kopff and Wild 2 offer future rendezvous opportunities.



Engineers and scientists from JPL and the University of Arizona's Lunar and Planetary Laboratory test the surface penetrator that will be one of CRAF's principal scientific instruments.

Cassini

The Cassini project is studying a mission to Saturn that would orbit the planet and drop a probe into the atmosphere of Titan, Saturn's largest satellite.

Early plans identified a Titan/Centaur as the launch vehicle, a Mariner Mark II spacecraft as the orbiter, and a probe to be developed by ESA. NASA and ESA would share mission operations and scientific investigations. Science payloads were defined in 1984–85: sixteen instruments would be placed on the orbiter and seven on the probe.

The JPL team completed mission and system design this year. Given a 1995 or 1996 launch, Earth and Jupiter gravity assists will permit the craft to arrive at Saturn in 2002. Several asteroids are candidates for flybys en route to Saturn. The probe would enter Titan's atmosphere after one orbit of Saturn, and the orbiter would continue for 30–40 orbits, encountering Titan several times. Gravity assists from Titan and other satellites would change the spacecraft's orbit, permitting investigation of Saturn and the rings at inclinations up to polar orbit, and of the other icy satellites as well.

Mars Rover Sample Return

The Laboratory undertook the leading role with NASA's Johnson Space Center to study a Mars Rover Sample Return mission that will collect samples of Mars' soil and bring them back to Earth. The mission would be a precursor to manned Mars exploration.

The Mars Rover Sample Return mission would include a vehicle to collect the soil samples. The study is examining designs for a rover that could travel between 100 yards and 100 kilometers from its lander. The

lander/rover would evaluate samples for transport to Earth, and would conduct on-site investigations.

Thousand Astronomical Units

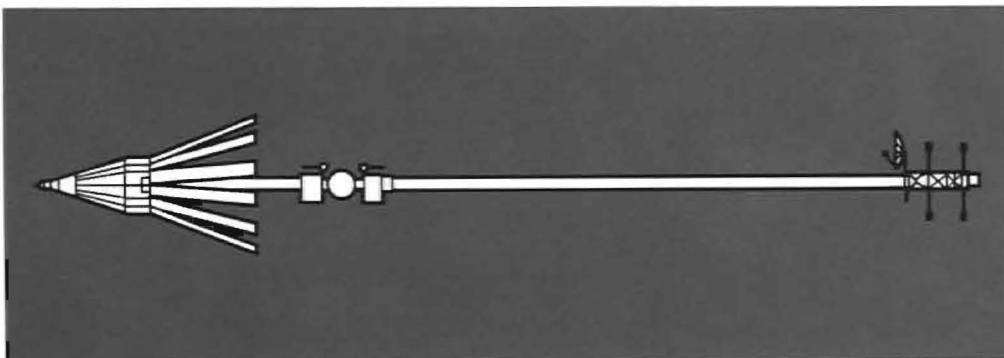
The Thousand Astronomical Units (TAU) mission concept envisions launching a large, unmanned spacecraft or two complementary spacecraft from Earth orbit early in the next century. The craft would be assembled and launched from the Space Station. TAU would fly under power for 10 years to reach a velocity that would carry it 1,000 astronomical units (9 billion miles) from the Sun in another 40 years.

TAU would sample the environment of the distant outer solar system and, perhaps, the interstellar medium. The increasing distance from Earth would serve as a baseline for measuring the distance of visible stars, infrared objects, and radio sources in the Milky Way and perhaps as far as the Magellanic Clouds, increasing the base of astronomical knowledge.

Studies by a small team of scientists at JPL identified scientific goals and candidate instruments, as well as conceptual design ideas for the mission, vehicle, and spacecraft and requirements for technology development.

The baseline mission would use a heavy-lift launch vehicle to deliver parts to orbit for assembly and launch in the first decade of the 21st century, a launch mass more than 60 tons, and a 10-year thrust phase using xenon ion engines powered by a one-megawatt nuclear reactor.

Two key technologies are nuclear electric propulsion and laser communications. The xenon ion propulsion, optical communications, and hardware designed for half a century of operating life still must be developed and engineered.



A diagram of the TAU spacecraft shows its nuclear reactor, left, ion-propulsion module, center, and payload module, right. The spacecraft's total length is 122.5 meters.

EARTH-ORBITAL MISSIONS

TOPEX/Poseidon

NASA and the French space agency, Centre National d'Etudes Spatiales (CNES), agreed to conduct the TOPEX/Poseidon mission to study sea levels and ocean currents, using radar altimetry. Both agencies authorized the project start in fiscal year 1987.

The contract to build the U.S.-supplied satellite was awarded to Fairchild Space Company in May. The satellite will be launched on an Ariane rocket from Kourou, French Guiana, in December 1991. TOPEX will operate in an 830-mile, 63-degree-inclination orbit.

JPL will provide a two-channel radar altimeter and a microwave radiometer to correct for atmospheric effects. France will fly an experimental solid-state radar altimeter. The spacecraft's exact position, to within five inches, is important to the ocean studies; both U.S. and French tracking systems will be used.

In September NASA selected 20 scientists, and CNES selected 18, as principal investigators for the studies to be carried out using data from TOPEX/Poseidon. Researchers will calculate the ocean circulation. The calculations will be useful in improving weather forecasting and planning for pollution control and offshore and coastal development worldwide.

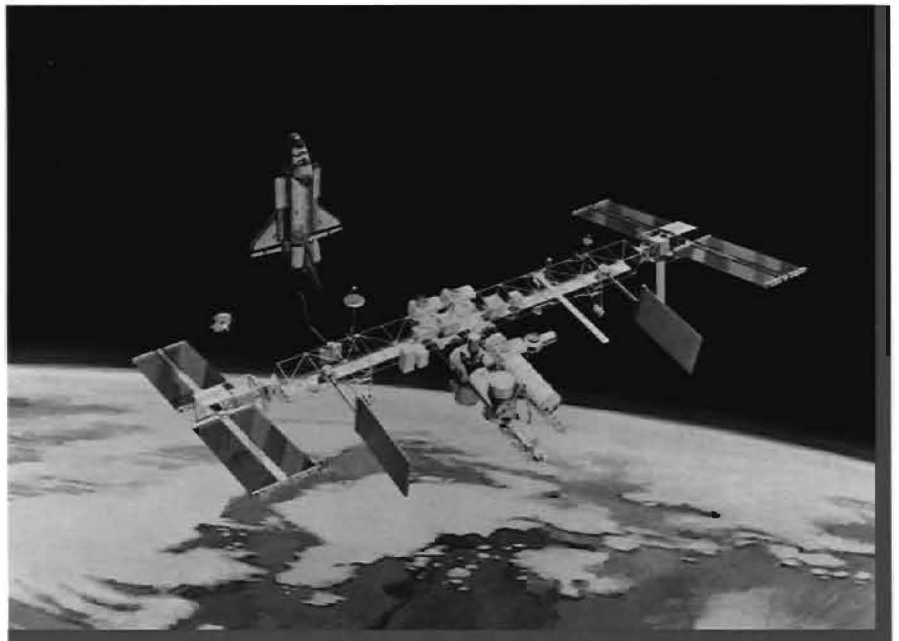
NASA Scatterometer

The NASA Scatterometer (NSCAT) project is developing a backscatter radar instrument and ground data-processing system to produce frequent, high-resolution measurements of near-surface wind speed and direction over the oceans. NSCAT will fly at the same time as TOPEX and the two will work in tandem.

The Science Definition Team, composed of oceanographers and meteorologists selected by NASA in 1986 to use the wind data from NSCAT, met twice at JPL on design and performance issues.

The Harris Corporation in Melbourne, Florida, completed a subcontract for six flight antennas and one spare, which are being tested at JPL. Instrument electronics were designed at JPL and the digital and radio-frequency circuitry is being tested at JPL and at Harris.

Prototype computer software for data-processing algorithms is complete and performs well. And preparations have been made to procure a large data-processing computer in mid-1988.





McDonnell Douglas

Space Station

JPL took on a major role for NASA's Space Station project by establishing the project facilities in Reston, Virginia, and by leading the program requirements and analysis (PR&A) effort as a member of Space Station level II management. Some JPL technical support activity remains in Pasadena.

The PR&A Office has been staffed, principally with senior system analysts and system engineers. It participates in program management, including leadership of the Program Plan effort, responsibility for the Program Requirements Document, and support for generating and revising the Program Approval Document.

The Requirements Document, PR&A's first major task, is close to the needed baseline version; Program Plan work began at year's end. Other tasks include developing a cost-management process and analyses and assessments.

People test an active module of the Space Station, designed by McDonnell Douglas for NASA. Here astronauts would eat, exercise, bathe, and relax when not working. The painting at left shows the Space Station orbiting Earth.

SPACE AND EARTH SCIENCE

■ New scientific knowledge is the final aim of all JPL activities, and this year's work brought important new knowledge and understanding of Earth and the solar system's other planets, and of interstellar space, as well.

SOLAR SYSTEM EXPLORATION

Planetary scientists continued to observe and analyze planets, satellites, asteroids, and comets, largely using infrared and radar spectra.

Astronomers used the great antenna at Arecibo Observatory in Puerto Rico to study the near-Earth asteroid 1986 DA. The conclusions are that the asteroid may be metallic and that its surface is smooth, irregular, and has little or no porous material.

The main-belt asteroid 130 Elektra, observed from NASA's Infrared Telescope Facility in Hawaii, appears to contain hydrocarbons and to be similar to some carbonaceous chondrites.

And JPL continued as lead center for the International Halley Watch, archiving data from worldwide observations of Comet Halley.

The Halley Watch group is still compiling data on the 1985 appearance of Comet Giacobini-Zinner and the 1986 return of Comet Halley. Giacobini-Zinner data will be published in late 1988. Data on Comet Halley will be published as a 3,500-page book in 1989 and as compact disks of 20 gigabytes in 1990.

Jupiter's Tropospheric Clouds

Studies of deep clouds in Jupiter's atmosphere show that they vary markedly in altitude over the planet. The clouds appear to be water or ammonia hydrosulfide and to lie under an obscuring stratospheric haze or smog layer and a thick cloud of ammonia-ice particles.

To observe the troposphere, JPL and Washington University astronomers used the Table Mountain and Mauna Kea Observatories to gather infrared data. The data contain spectral lines of ammonia gas. Over an 18-month period, the astronomers obtained three global ammonia maps of Jupiter. Gaseous ammonia is considered a good indicator of conditions below the ammonia-ice clouds.

Jupiter is marked by a series of relatively dark belts alternating with lighter zones, all parallel to the equator. The pattern appears to

show the atmospheric structure below. The map of ammonia-gas pressure at the tops of the tropospheric clouds indicates the clouds' altitudes.

The data confirm the long-held hypothesis that Jupiter's light-colored zones consist of rising columns of ammonia-rich air, while the belts are subsiding and are ammonia-poor. Continued monitoring and analysis of such features will take place during Galileo's atmospheric probing in 1995.

Volcanic Eruptions on Io

Since the first observation of volcanic activity on Jupiter's satellite Io by Voyager 1 in 1979, a JPL team has used Earth-based telescopes to measure infrared radiation from the satellite to map hot spots and study the evolution of Io's volcanic activity. The problem is that even with large telescopes, Io's surface cannot be seen very clearly from Earth. However, every six years we pass through the orbital plane of the Galilean satellites. Then another large, colder satellite passes between Io and Earth and covers Io's disk. Comparing successive measurements of infrared radiation permits a radiometric sweep across the disk. The team can locate and measure sizes and temperatures of active hot spots from the drop in intensity as each hot spot disappears behind the other satellite, and the increase in intensity as Io emerges later.

Astronomers from JPL and the University of Hawaii have measured Io's disk through seven occultations, to map the hot spots.



The map covers more than 90 percent of the surface. Features include Loki, the largest hot spot (about 270 kilometers across, temperature 340 K). Loki is north and east of Loki Patera, which Voyager mapped. Another feature is a small, hotter spot on Io's leading hemisphere. A third feature appears to be small and very hot (less than 2 kilometers in diameter, temperature 1150 K). It could be the first direct evidence of exposed silicate magma.

In an independent long-term program of monitoring Io's infrared brightness at several wavelengths, a major outburst was observed: total brightness at three shorter wavelengths rose to 1.5–2.5 times normal. The 20-micron brightness remained unchanged. Preliminary interpretation suggested a 30- to 40-kilometer spot at a temperature of 800–900 K.

JPL astronomers continue observations of the dynamic Io, to study volcanic processes and to provide data for Galileo's flyby of Io as the spacecraft approaches Jupiter.

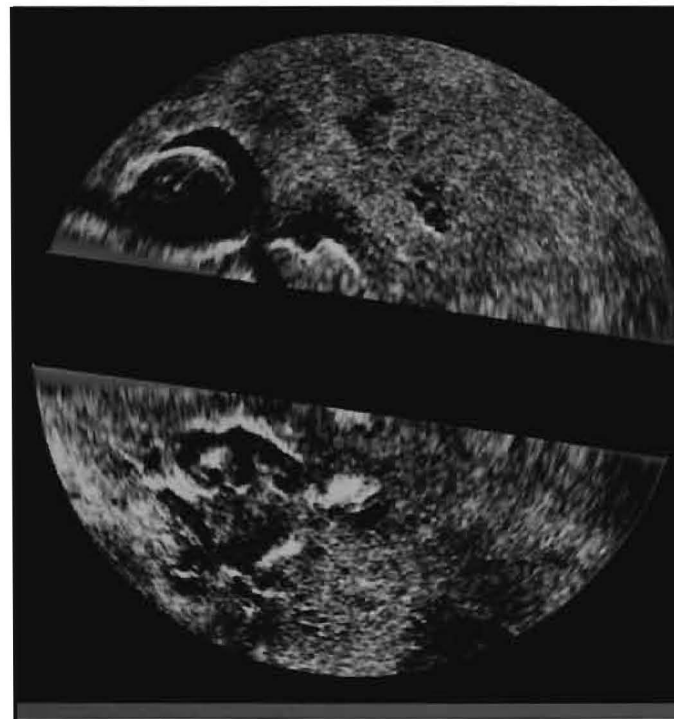
Goldstone Solar System Radar

Planetary radar astronomers continued to observe a variety of objects in the solar system. Radar signals were bounced off the Moon, Mercury, Venus, Mars, the asteroid Midas, the Galilean satellite Callisto, and Saturn's rings.

Radar observations of Venus made in 1986, when Venus passed between the Sun and Earth, and processed this year, yielded images with a resolution of about 1.3 kilometers. The images are comparable to those from the Soviet Venera 15 and 16 spacecraft and are the highest resolution images ever obtained with Earth-based radar interferometry. The images will provide geological information and benchmarks, as well as data for determining the direction of Venus' poles with greater accuracy than was possible before.

We also made extensive observations of Mars, of the same sites viewed in 1971 and 1973. The work will assist with future NASA missions to Mars.

An observational highlight of the year was an experiment using Goldstone antennas and the antennas of the Very Large Array at Socorro, New Mexico. Echoes from Saturn's rings were detected. The echoes will yield direct two-dimensional mapping data on the rings.



This radar image from Goldstone, California, shows a portion of the central disk of Venus. The black band in the center is an artifact of the data processing.

Pluto's Atmosphere

Analysis of the data from the Infrared Astronomical Satellite and three years of Earth-based observation suggests that Pluto's atmosphere is much denser than we had believed. Such density, however, does not fit the pattern of outer planets as to orbit, size, or other characteristics.

JPL and University of Arizona planetologists analyzed the data, which show that Pluto is different from asteroids and the icy satellites of giant planets. Pluto's temperature might indicate a significant atmosphere. Methane was the only constituent found, but neon or argon, not detectable at Pluto's great distance, may be present, too.

The study also provided precise measurements of the diameter of Pluto (2,200 kilometers) and of its satellite, Charon (1,300 kilometers).

EARTH SCIENCE

Earth is just one of the nine planets in the solar system—but it is the only planet capable of supporting life. Therefore, JPL scientists study Earth's atmosphere as one example of a planetary atmosphere.

During the year, JPL scientists and engineers investigated the recently discovered hole in Earth's ozone layer over the Antarctic. The work included laboratory experiments, participation in an expedition to the South Pole, and development and flight of advanced instruments.

Ozone in Earth's Upper Atmosphere

Of growing concern is the prospect that chlorine and perhaps other chemicals, released into the atmosphere by human activities, are depleting the natural ozone layer, which acts as a shield against solar ultraviolet radiation.

In 1985, British scientists reported a large hole in the ozone layer over the Antarctic. The hole has appeared each southern spring since then. An expedition this year, the Airborne Antarctic Ozone Experiment, studied the ozone hole. Participants were NASA, the National Oceanic and Atmospheric Administration, the National Science Foundation, and the Chemical Manufacturers Association.

Scientists had debated three possible causes for the hole. One set of theories says the hole is caused by natural movements of air. A second involves nitrogen oxides that are produced naturally. The third set implicates chlorine from man-made chlorofluorocarbons that are released into the atmosphere.

The scientists suspected chlorine, released into the atmosphere as chlorofluorocarbons, as the culprit; but they were unable to reproduce the exact set of chemical reactions that would cause ozone depletion. This year chemists from JPL performed laboratory experiments that showed exactly how chlorine is liberated from hydrochloric acid, so that sunlight can then break down the chlorine. Free chlorine is then able to attack the ozone layer.

Combined with data from the Antarctic expeditions, the laboratory data show that natural or dynamic forces alone could not create the ozone hole, although the forces appear to play an important part. The theories

involving naturally produced nitrogen oxides also were ruled out.

In the JPL group's scenario, some chlorine becomes chlorine monoxide, which in turn reacts with other chlorine monoxide to form a special molecule (called a dimer) of chlorine and oxygen. The new molecule then undergoes more reactions that can eventually result in release of two single chlorine atoms. The single chlorine atoms then react with ozone to create chlorine monoxide and molecular oxygen. The result is that two ozone atoms have been turned into oxygen, and the chlorine monoxide is left to start the process anew.

Antarctic Ozone Expedition

The Airborne Antarctic Ozone Experiment furnished further evidence linking chlorine to the annual appearance of the ozone hole. JPL scientists flew an experiment that showed direct correlation between seasonal temperature changes in the Antarctic and growth and recession of the ozone hole.

The JPL group discovered that chlorine may hibernate in a condensed phase in stratospheric clouds over the South Pole during the frigid Antarctic winter. When the air warms in springtime, the chlorine emerges from hibernation in a reactive, ozone-destroying vapor.

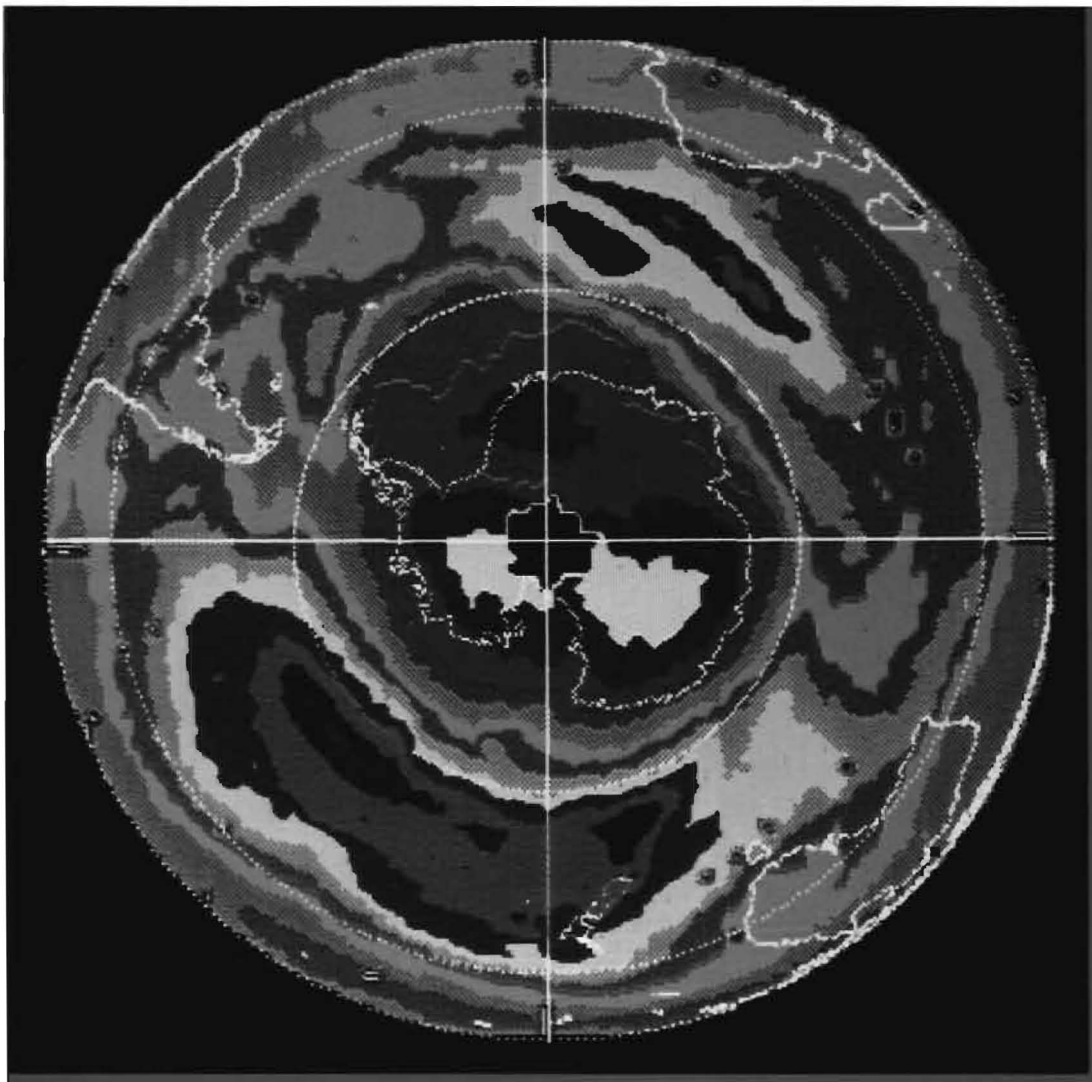
Between August and November, there was about 40 percent less ozone in the Antarctic stratosphere, compared to levels in the late 1960s and early 1970s. In late November the ozone level returned to normal.

Two advanced instruments being developed at the Laboratory have specific application to studies of Earth's ozone layer.

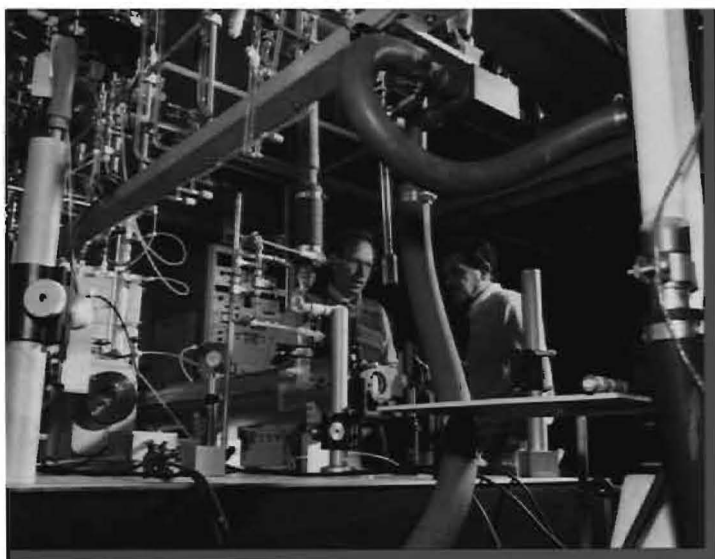
Microwave Limb Sounder

In further support of the ozone-hole studies, JPL scientists flew their balloon-borne microwave limb sounder twice.

The instrument measured ozone and chlorine monoxide simultaneously between 10 and 20 kilometers in altitude for more than 30 hours during one flight and 12 hours during the other. Early analysis of the data indicated lower peak values of chlorine monoxide than theories predict. Similar results came from earlier flights. The discrepancy is as yet unresolved.



This plot of the distribution of ozone over Earth's southern hemisphere was made from data gathered by an instrument on Nimbus-7.



JPL scientists run laboratory experiments to confirm the chemical reactions that threaten Earth's ozone layer.

Another microwave limb sounder is also being developed for the Upper Atmosphere Research Satellite, scheduled for launch in 1991. JPL is responsible for the experiment, and the British are providing a 183-gigahertz radiometer and analysis of the data. This year engineers completed a vibration-test model and began integration of the flight model.

Balloon Infrared Laser Spectrometer

A flight in May of the Balloon-Borne Laser In Situ Sensor marked the third consecutive flight in 18 months of the high-sensitivity spectrometer, and the first test flight of a new balloon material for upper atmosphere payloads.

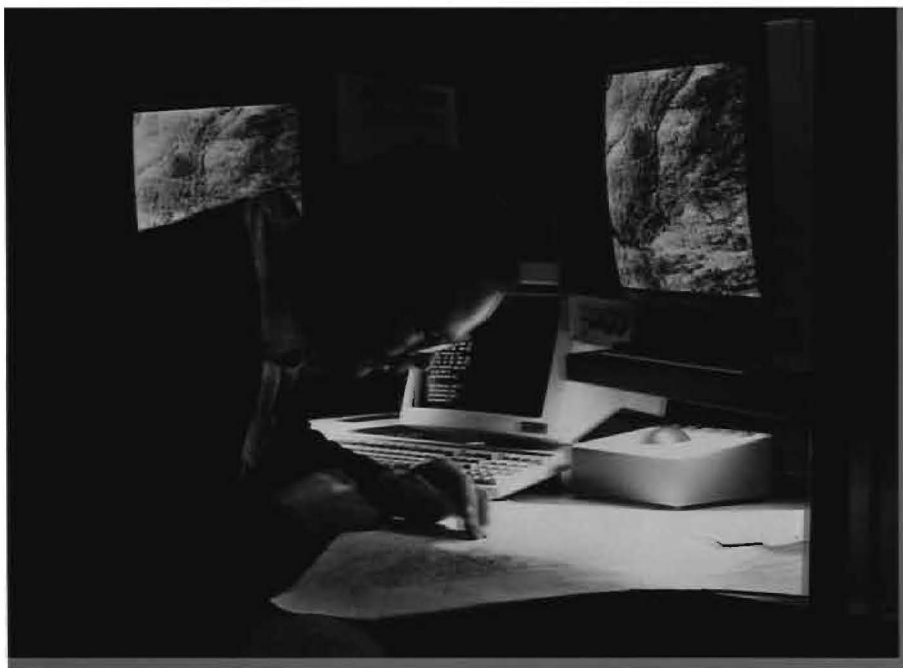
To assess more precisely the extent to which human activity can modify the ozone layer of the stratosphere, upper-atmospheric studies are emphasizing a new strategy of data collection that requires simultaneous measurement of several chemically related species, including ozone.

The instrument uses a new approach to making such simultaneous measurements of the stratosphere's composition. At flight altitude, about 30 kilometers, a laser beam tracks a retroreflector lowered almost 500 meters

below the gondola that carries the laser. Signals from tunable, solid-state diode lasers bounce off the retroreflector so that infrared measurements can be made to determine gas concentrations at the sub-parts-per-billion level.

The spectrometer was flown from Palestine, Texas, in May and measured nitric oxide, nitrogen dioxide, ozone, water vapor, and methane. The instrument flew again in October to measure the nighttime decay of nitric oxide. The most interesting data of the October flight was the observation of an increase in nitric oxide during the morning at the expense of nitrogen dioxide. The depletion was linked to sunlight reactions.

Engineers and scientists are developing a related instrument for the Cassini mission, which will orbit Saturn and drop a probe into the atmosphere of Titan. A miniature infrared spectrometer, whose retroreflector is only eight inches from the lasers and detectors, is designed to measure many gases, clouds, and isotope ratios.





Laser beams from Table Mountain Observatory measure changes in the stratosphere.

Laser Atmospheric Sounding From Table Mountain

NASA is developing a ground-based, long-term monitoring network for the earliest possible detection of changes in composition and structure of the stratosphere, such as occur in the ozone layer above Antarctica. To support the network, a laser remote-sensing facility has been set up at JPL's Table Mountain Observatory in the San Gabriel Mountains 60 miles northeast of Pasadena.

The facility uses high-power lasers to probe the atmosphere from the ground to altitudes of about 100 kilometers. Primary emphasis is on the stratosphere (15–30 kilometers above sea level) and ozone is the most important species being measured. The system transmits laser-light pulses at two ultraviolet wavelengths and uses differences in absorptions of ozone to take an ozone concentration profile. The technique is called differential absorption lidar (lidar is the laser equivalent of radar) and it is used to measure aerosols and temperature profiles in the atmosphere.

The network will acquire long-term data so that small trends underlying large natural variations can be observed. The measurements

will provide early warnings of stratospheric changes caused by human activities and should enhance understanding of stratospheric processes.

Shuttle Imaging Radar-C

Shuttle Imaging Radar-C (SIR-C), the next step in the Laboratory's Spaceborne Imaging Radar program, will fly aboard the shuttle in January 1991 and July 1992. SIR-C will support geoscience studies that need synthetic-aperture-radar data from orbit, not obscured by clouds, vegetation, or alluvium. Results will improve understanding of Earth's surface locally and, through integration into global modeling, at planetary scale.

SIR-C scientists and engineers completed the design and held a preliminary design review in November. Proposals for research using SIR-C data were sent to NASA for review and selection in mid-1988. The SIR-C group also completed the Airborne Synthetic-Aperture Radar, the prototype system designed for testing and operations by aircraft. Its first engineering flight was to be held in January 1988.



AVIRIS captured this image of Rogers Dry Lake and Edwards Air Force Base from 60,000 feet.

Airborne Visible and Infrared Imaging Spectroscopy

After three years, the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) completed engineering flights in early 1987 and began to collect data in the summer.

AVIRIS was designed for flight aboard NASA's ER-2 aircraft at an altitude of 60,000 feet. The instrument senses 224 bands from the violet into the infrared (0.41–2.45 microns). AVIRIS is a precursor to satellite instruments and has begun to demonstrate improved capabilities for remotely sensing Earth, for botanical, geological, hydrological, and oceanographic purposes. AVIRIS will have applications such as resource and environment management, agricultural development, and mineral exploration.

Mapping Ocean Eddies From Satellite Altimetry

The most energetic component of ocean circulation is composed of eddies about 100 kilometers across that last as long as a month. Unstable ocean currents generate the eddies, which are the oceanic counterpart of cyclones in the air. The eddies help transport mass, momentum, heat, and nutrients in the ocean. Mapping the evolution of eddies on a global scale has been an important but difficult goal for oceanographers.

JPL scientists used observations of sea-surface height from the radar altimeter aboard Geosat to show that eddies can be mapped from space. The method has been used to produce sequential maps of eddies. Scientists

at JPL and the National Center for Atmospheric Research use the maps to study the dynamics of ocean eddies. Results of the study will help demonstrate the utility of the TOPEX/Poseidon mission, which will perform altimetry with a much higher accuracy than Geosat.

Sensing Forest Damage From Orbit

A group of scientists used data from the Landsat D Thematic Mapper to determine if the instrument can detect and measure damage to forests from pollutants such as acid rain.

The principal study region was Whiteface Mountain in New York's Adirondack Mountains. More work was done in other parts of the Adirondacks, as well as the Green Mountains and White Mountains. On Whiteface Mountain, an area of extremely high mortality of fir and spruce trees lies between the 800- and 900-meter elevations.

The data appear to show more damage to trees on western slopes of the mountains than on other sides. That could be caused either by harsher winter conditions on the western slopes or by more exposure to pollutants carried on the westerly winds. A 1982 study of rainfall acidity for the northeastern United States found the highest acidity over the Adirondacks. Acidity decreased toward the east. On the basis of this year's findings, the scientists believe that spaceborne instruments will be able to monitor forest conditions over large regional areas.

Aurora Formation Mechanism

Scientists had long believed the aurora borealis (or northern lights) is a result of decaying solar storms. Data from the JPL magnetometer on the International Sun Earth Explorer-3 show that a different process is involved.

The aurora borealis and a similar South Pole phenomenon, aurora australis, are caused by Alfvén-wave trains from the Sun. The waves cause directional changes in the interplanetary magnetic field. When the wave field is opposite to the northward direction of Earth's magnetic field, magnetic reconnection occurs, transferring solar wind energy into the Van Allen radiation belts. Instabilities in the radiation belts cause ionized particles to scatter and follow the Earth's magnetic-field lines toward the surface at the poles. Electrons and ions strike atoms in the upper ionosphere and make them emit light—the characteristic wavy displays of the aurora.

Telecommunications-Based Geodesy and Geodynamics

JPL scientists and engineers made major advances in instruments and data-analysis techniques to develop a high-precision system for regional geodesy based on NASA's Global Positioning System (GPS) satellites. JPL's other interests in GPS include reducing uncertainties in the locations of Deep Space Stations and determining the precise location of Earth-orbiting spacecraft like TOPEX.

In geodetic applications, mobile receivers that were designed to track and process signals from the GPS satellites are located relative to a series of benchmarks. The JPL system allows determination of the benchmarks' locations to a precision of one part in 100 million.

During the year, we completed preparations to use the system in an ambitious campaign of geodetic measurements scheduled

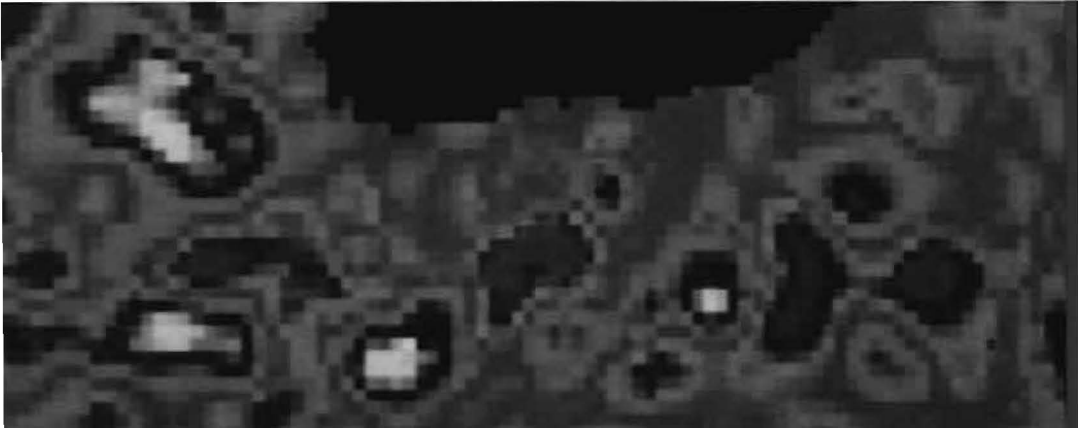
for January and February 1988. The preparations included experiments that use five sites in the United States and Mexico, along with the six satellites that have been deployed. Results for GPS-8, which was tracked the longest, showed one-meter agreement.

In the experiment, 25 GPS receivers will be placed in Central America, northwestern South America, and islands in the Pacific and the Caribbean, a geodetic network that spans the region where the Nazca, Cocos, Caribbean, and South American plates meet. Results will help measure rates and character of tectonic processes in that part of the world.

Data acquisition at the receiver sites will be accompanied by simultaneous data acquisition at sites in a fiducial network in the United States. (Fiducial sites establish a precise, fixed reference frame for the GPS-based measurements.) The network will be expanded to include receivers in Europe and the South Pacific.

The experiment is conducted by an international group that includes the United States, Germany, Norway, Switzerland, Canada, Colombia, Venezuela, Ecuador, Costa Rica, Panama, Australia, and New Zealand.

Scientists at JPL continued their studies of global geodynamic processes using data from lunar laser ranging and very long baseline interferometry. Lunar laser ranging involves measurement of the round-trip time of flight of laser light between Earth and retroreflectors placed on the Moon by Apollo astronauts. The results are used to study interactions between Earth's core and its mantle. Recent developments include the discovery and study of rapid motion of the Earth's spin axis with respect to the crust.



The digital map was made from satellite data and shows the dynamics of large ocean eddies.

ASTROPHYSICS

Supernova 1987A: Radio Observations

On February 23, a naked-eye supernova appeared in the Large Magellanic Cloud, a galaxy in the southern sky. Supernova 1987A was the closest object of its kind that has been observed in 383 years. The DSN performed radio-astronomy studies of the exploding star through the year and obtained a measurement of its expanding shell.

Within hours of the supernova's discovery, astronomers began observations using the 64-meter antenna at Canberra. The antenna teamed with Australia's 64-meter Parkes radio telescope, using the microwave link that had supported Voyager's encounter with Uranus. The system detected a weak radio outburst that faded after several days. The source has been quiet since its first low-level burst. If SN1987A follows the pattern of other supernovae, however, its radio emissions may be shielded by matter that was ionized in the explosion. When the shield dissipates, SN1987A may become one of the sky's brightest radio sources.

During the initial radio outburst, very long baseline interferometry observations were carried out between Canberra and the 26-meter Hartebeesthoek antenna in South Africa to provide the first direct measurement of the size of the supernova's expanding shell. Five

days after the explosion, the shell had a diameter greater than 1.5 billion kilometers. An array of five Australian antennas, including the large DSN antenna, will try to make high-angular-resolution images of the shell when its radio emission reappears.

Gamma-Ray Emission From Cygnus X-1

A JPL gamma-ray telescope has observed strong gamma-ray emission from Cygnus X-1. Astronomers have long believed Cygnus X-1 is a black hole, an object that was predicted by Einstein's General Theory of Relativity.

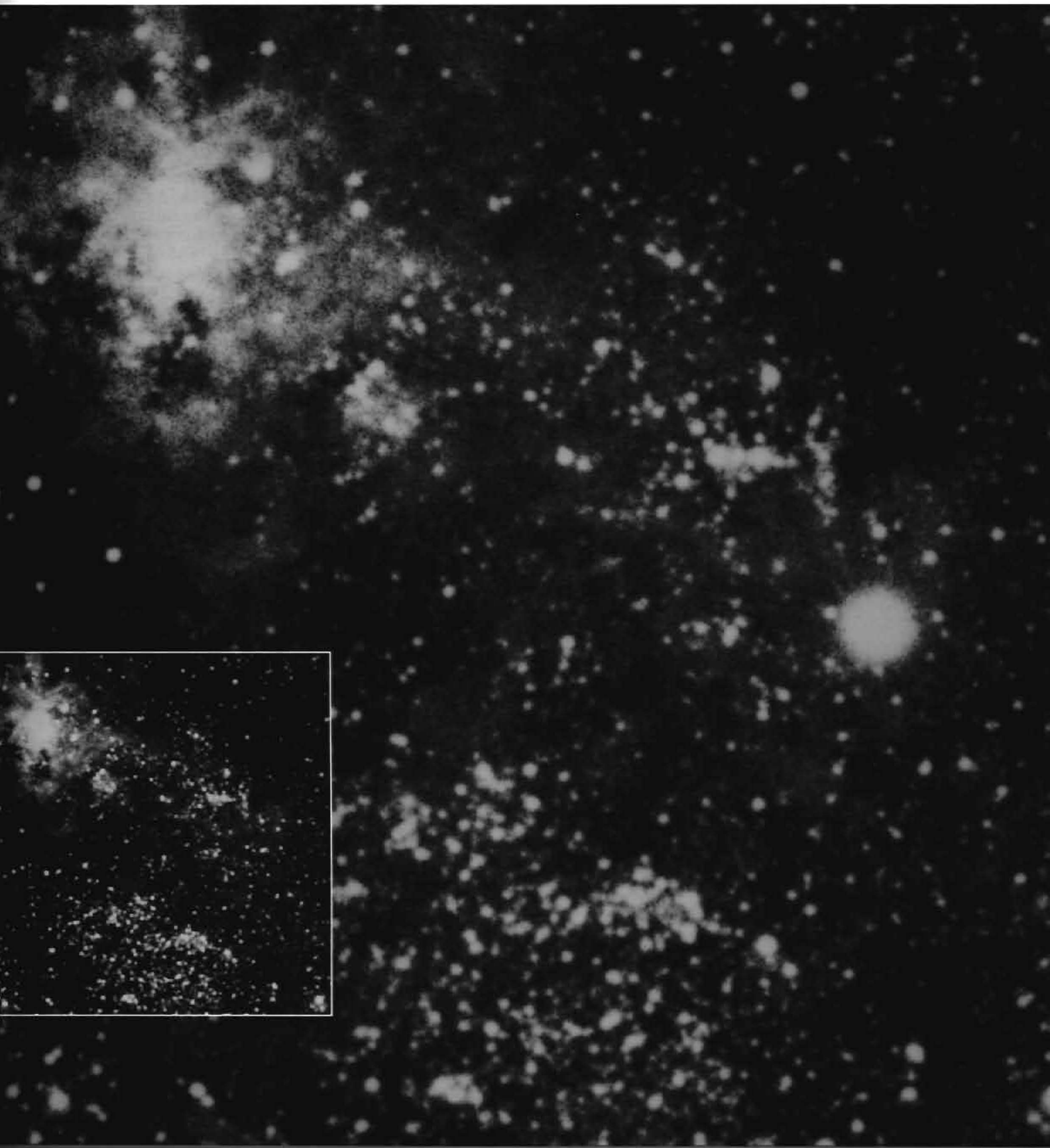
Scientists believe black holes originate in explosions that occur when massive stars exhaust their nuclear fuel. Black holes also exist at the center of galaxies like the Milky Way. Gamma rays are strong evidence that antimatter is created in the hot, innermost region of a disk surrounding a black hole.

X-ray astronomy has established a class of neutron stars, collapsed stars whose gravitational field attracts and heats gas from a nearby star, producing X-rays. However, neutron stars do not usually produce gamma rays.

Cygnus X-1, whose mass is about three times the maximum thought possible for a neutron star, is similar to active extragalactic objects, and the Milky Way's center.



Light from Supernova 1987A (bright spot at center right) traveled 170,000 years, and finally reached Earth this year. The exploding star, which had 20 times the Sun's mass, does not appear in the 1984 photo (inset).



ADVANCED TECHNOLOGY

■ Advanced technology gives us the tools with which we can do our job. Development of new technology is one of the leading roles that the Laboratory performs for our nation.

JPL looks for the kinds of technology that we can do uniquely and that satisfy the requirements of our missions. We then single out those special areas of effort and create technology thrusts to secure the benefits of rapid advances in those technology areas for NASA's unique needs. Technology thrusts receive special attention in the form of discretionary funds, recruiting efforts, and the creation of laboratory facilities.

Each technology thrust, then, is overseen by a Technology-Thrust Leader, who coordinates technical efforts, fund-raising, and facilities planning.

Currently the Laboratory has technology thrusts in two areas: space microelectronics technology and automation and robotics (A&R).

TECHNOLOGY THRUSTS

The Center for Space Microelectronics Technology

On January 21, a Memorandum of Understanding between NASA and Caltech established the Center for Space Microelectronics Technology (CSMT) at JPL. The CSMT provides long-range supporting research and development in advanced microelectronics for a wide range of space-related efforts, particularly for NASA and the Department of Defense. The center conducts research and development in solid-state devices, pho-

tonics, custom microcircuits, and computer architecture.

CSMT's goal is to provide technology essential to future space flight. At NASA's request, in 1983, JPL had established the Advanced Microelectronics Program to do research that is unique to the tasks of JPL, NASA, and DOD. The Center for Space Microelectronics Technology replaces the Advanced Microelectronics Program.

The Caltech faculty takes a strong participatory interest in the center. A Board of Governors provides policy guidance and program oversight. The board includes senior managers from NASA, Strategic Defense Initiative Organization, Defense Advanced Research Projects Agency, JPL, and Caltech.

Ground was broken on January 21 for the Microdevices Laboratory (MDL), which will be a primary facility of the CSMT. The MDL is a 38,000-square-foot, three-story building. It has clean rooms, laboratories, and offices for 60 employees, and two conference rooms. The laboratory will be filled with \$11.4 million worth of equipment for fabricating advanced sensors and other microelectronic devices.

CSMT's solid-state-device research activities will be located in the new building. Devices created in the MDL will be turned over to industry for manufacture. Work in the center will be unclassified and research will be published.

This photo shows the four steps in the design, construction, and analysis of an IUS adapter longeron for Galileo. At top is a stress-analysis image produced in a computer model of the hardware. Next is the design produced on a computer-aided-design terminal. Just below is the tool-path model and at bottom is the actual longeron. In the first such milestone of its kind for the Laboratory, the longeron was engineered, designed, manufactured, and then analyzed for stress by computer.



The \$9 million laboratory should be ready for occupancy in May 1988.

Solid-State Device Research. There are four major specialties under the solid-state devices program. First is the design and fabrication of materials that consist of multiple layers of differing semiconductor materials that, in combination, provide unique electrical or photodetection capabilities unavailable in today's microelectronic semiconductors. The engineered materials will allow us to make advances in two fields: new sensors for the focal planes of our advanced observational instruments in the infrared region of the spectrum, and new arrays of solid-state lasers for interplanetary optical communication.

The electron tunneling accelerometer is a new use of the electron-tunneling phenomenon, which grew out of JPL's research on the scanning tunneling microscope. The new technology is a new operating principle for accelerometers, which are widely used in aircraft, missiles, and spacecraft. The electron tunneling accelerometer is expected to be 100 to 1,000 times more sensitive, more than 100 times less expensive, and to require less than 1/100th of the power of the best conventional accelerometers now available. JPL has begun a collaborative development program with the Charles Stark Draper Laboratory of Massachusetts Institute of Technology.

A JPL scientist invented a new way of using the scanning tunneling microscope, called ballistic electron emission microscopy. In the past, the scanning tunneling microscope was used to make images of individual atoms on the outermost surfaces of solid materials. We had thought that surface imaging was the fundamental limitation of the microscope. Now JPL researchers have shown that proper adjustment of spacing and voltages in the microscope allows us to image interfaces buried 100 atomic layers beneath the surfaces of solids. Since the new technique will allow us to look inside the bulk of semiconductor materials, it will be an important tool for examining those interfaces, which control the performance of all semiconductor devices

The second major specialty is development of sensors for the submillimeter-wave range of the spectrum based on thin-film devices made of superconducting metals. We cannot see the universe in the submillimeter region of the spectrum from Earth's surface, since the atmosphere blocks out that radiation. Superconducting-sensor technology will enable us to design and build the submillimeter-wave space observatory called the Large Deployable Reflector (LDR).

In the third CSMT specialty, optoelectronic devices, which use an electronic signal to modulate light, are being developed to support many space applications. They include interplanetary optical communications and optical computing. Optical computing is a technique for conducting computational operations by switching light beams, in contrast to switching electronic currents, the method of computing used in conventional digital computers. Some of the advantages of optical computing include highly parallel operations, the absence of a need for insulated wires (since light beams do not interact with one another as electric currents do), and the ability to work directly with spacecraft photographs, such as onboard processing of optical images.

In certain computing tasks, the noninteraction of light beams is a disadvantage: when we want one light beam to switch another light beam on or off, for example. We are currently investigating optically driven light modulators (or switches) that are based on compound semiconductor materials. The switches can allow a light beam of one color to switch another light beam of a different color on or off.

Previous research at JPL has shown that optical communication is the technology of the future for interplanetary data communication. Today's individual solid-state lasers are not powerful enough to do the job. Therefore, we require essentially a chorus of lasers, all singing together. Such devices are referred to as phase-locked arrays

We are developing phase-locked arrays that possess very low noise, and we expect to use them for interplanetary data communication and spaceborne optical radar.

CSMT scientists have been working for years on a technology known as artificial neural networks. They are computing devices based on new principles and are able to perform functions that are exceedingly difficult with conventional digital computers, such as image recognition and the understanding of messages from garbled or incomplete data. The artificial neural network concept was developed by Professor John Hopfield at Caltech. JPL has concentrated on developing hardware embodiments of Hopfield's theoretical ideas. Computation is based on a complex interconnection network between analog amplifiers. JPL has invented two new materials for use in the interconnection networks. The materials will allow us to electronically write and erase interconnection patterns, thus allowing us to build artificial neural networks that can learn from experience. We expect important applications in image processing, robotics, and communications for the devices.

The fourth area of CSMT specialty involves the custom design of integrated circuits, specialized for specific space applications. We are involved in the design of a chip to control the access to the Mariner Mark II spacecraft's computer memory. The chip is currently being considered for adoption by industry as a commercial product in the area of space electronics.

A second leading integrated circuit design is the creation of an advanced communication chip for later generations of the hypercube computer.

Fiberoptic Rotation Sensor. Since the dawn of space flight, a limitation on our ability to send a spacecraft where we want it to go has been the relatively inefficient mechanical gyro. Mechanical gyros suffer from the faults of any mechanical system—short lifetime, power consumption, weight, and cost.

JPL and others have sought to replace the mechanical gyro with an all-solid-state, no-

moving-parts gyro based on optical technology. JPL's initiative in the area is called the Fiberoptic Rotation Sensor. In the task, JPL is working in collaboration with AT&T Bell Laboratories.

We can sense the rotation of a spacecraft by using the phenomenon called the Sagnac effect, which is based on the known universal constant velocity of light. The effect can be compared to two groups of runners moving around a race track in opposite directions at precisely the same speed. If the race track is standing still, both groups of runners would hit the finish line at exactly the same instant. But if the race track itself is rotating in one direction during the race, one group of runners would reach the finish line before the other group. By measuring the time interval between the arrival of the two groups, we can calculate the rate of rotation of the race track.

In the JPL device, light beams play the role of the runners, and a circular optical fiber is the race track.

Since there are no mechanical parts and all calculations are done by solid-state electronics, we have overcome most of the problems associated with mechanical gyros.

Initial tests show that the fiberoptic rotation sensor can measure a rotation rate as slight as three revolutions per year.

Hypercube. The Hypercube Project, a joint effort by JPL and Caltech scientists and engineers, continued to be the focal point for research and development of hardware, software, and applications for concurrent computation. Five commercial firms (Intel, Ametek, Floating Point Systems, Titan Cescio, and Ncube) are designing and building hypercubes, based on principles developed in the Caltech-JPL program. Honeywell, SCI, and Floating Point Systems participated in technology-transfer activities to advance the state of the art. Motorola contributes advanced devices for experimental use at JPL and Caltech.



The Mark III Hypercube grows inside a laboratory at JPL. The circuit board at left is one portion of the Mark III computer at right, which will contain 128 nodes. Each node is the equivalent of a single, powerful computer. The Mark III's total computing power will exceed the most powerful supercomputers in use today.



The Hypercube Project began several years ago as a Caltech effort to increase computing power with large-scale parallel processing. The concept is to array a large number of small computers, called nodes, to work in parallel on complex engineering and scientific problems. More than 100 applications are running in a wide range of scientific and engineering disciplines. The prototype machine used circuit boards from personal computers to demonstrate architecture. The hypercube's power is expanded by using more nodes or increasing the computing power of individual nodes.

The project is in the third generation of hypercube hardware. The Mark III machine, which is being completed at JPL, has individual nodes nearly 100 times as fast as a VAX 11/780. The Mark III will contain 128 of the new nodes. Its total computing power will exceed the most powerful commercial supercomputers available.

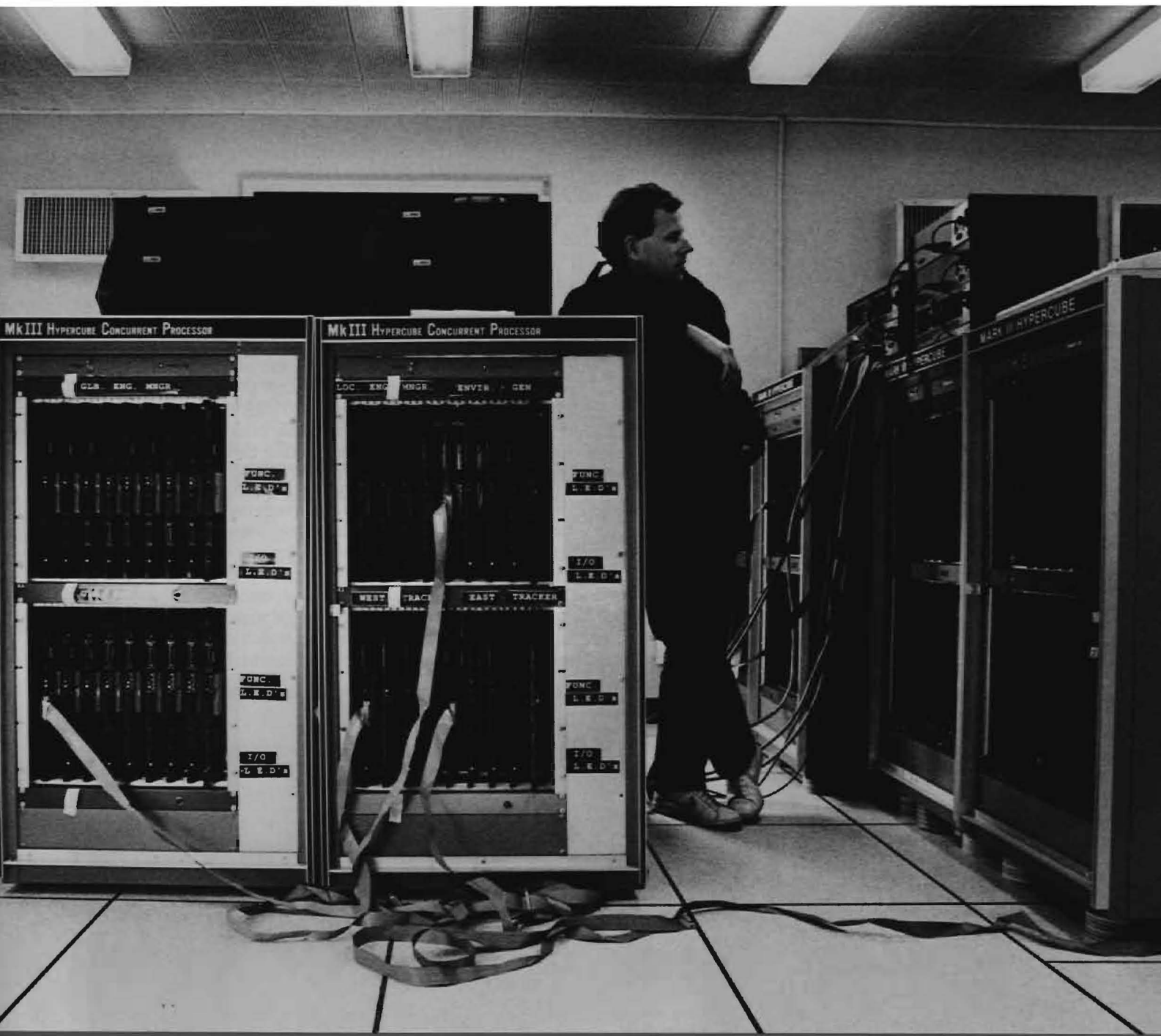
We have shown that the cost-effectiveness of the Mark III Hypercube is 10 times that of commercial supercomputers.

Machines of eight and 32 nodes are installed in JPL's Multimission Image Processing Laboratory and at Caltech for experimental use and for development of applications software.

JPL's work, in addition to applications programs, includes development of specialized operating systems for classes of problems that are interesting to our military and NASA sponsors. The Air Force Electronic Systems Command has provided major funding for the work.

For the future we hope to exploit the unique capabilities of the hypercube architecture for space-related problems. They include mission operations and onboard processing of sensor data in instruments and spacecraft.

The JPL/Caltech project team prepared to host the Third International Conference on Hypercube Concurrent Computers and Applications, to be held in Pasadena in January 1988. A dozen commercial firms will exhibit, and more than 250 presentations will be given before an expected crowd of 500.



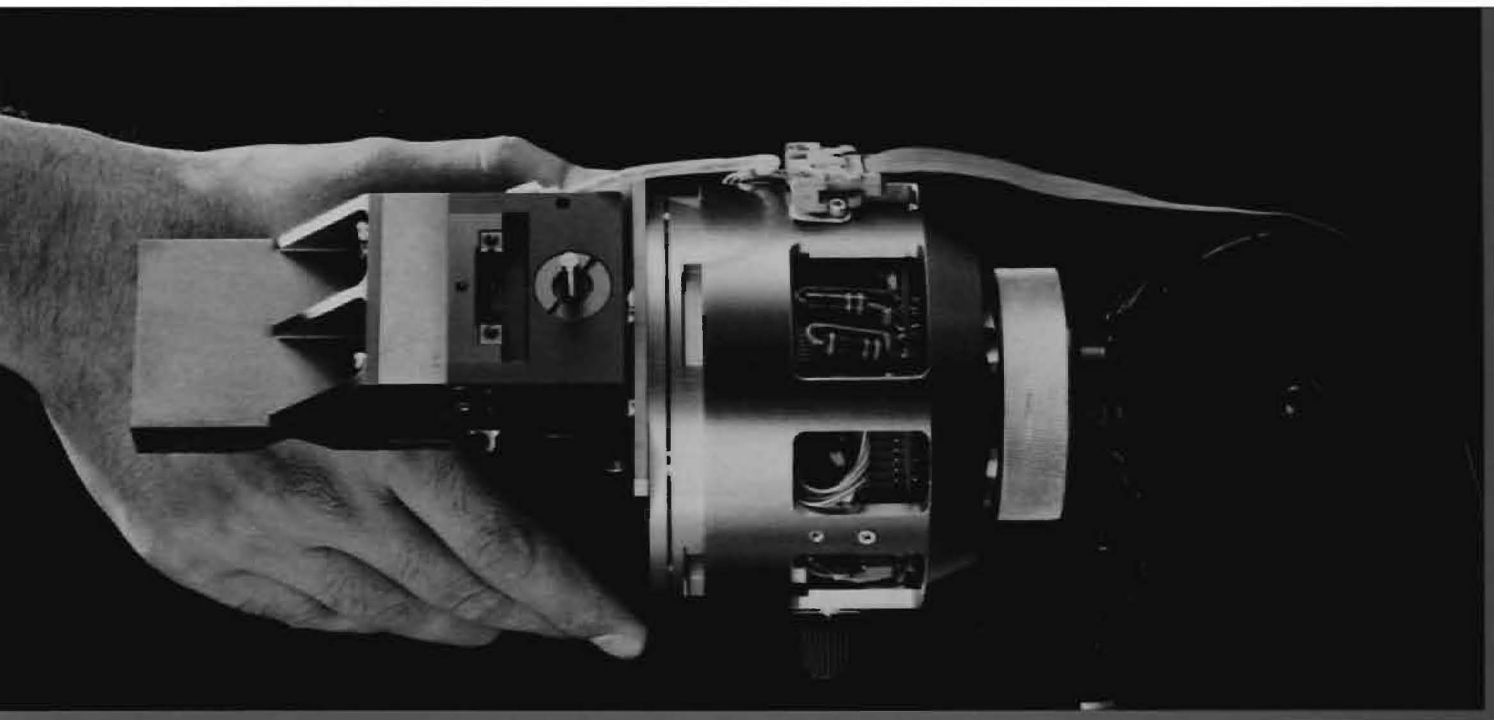
Automation and Robotics

JPL has been developing robotics technology for more than a decade and is one of the leading laboratories in the world. We foresee the need for enhanced teleoperation and robotics technology to accomplish such advanced missions as the Space Station and Mars Rover Sample Return.

While industry has concentrated its efforts on robotics in the workplace, JPL has always focused on the unique needs for robotics in space.

There are two parts to the A&R technology thrust. One is called teleoperation, which allows a human to work at a distance from the machinery, yet fully supervise the machine's actions. Robotics, on the other hand, involves the performance of tasks by the machine without full-time direction by a human.

One of the major projects in teleoperation is development of a force-reflecting hand controller. It is a handle with triggers and grips that allows an operator to manipulate a remote hand or arm that works, for example, on the Space Station. The controller is unique because it allows the operator to feel the actual forces that the remote arm is experiencing while it is manipulating an object. Thus the operator's own muscular skills can be called upon to perform the job better. For example, if a remote arm without the force-reflecting capability attempts to pick up an eggshell, it would almost certainly crush the shell. But with the force-reflecting capability, the operator can ensure that the shell is handled so gently that it would not be broken.



In order of difficulty, the next step in A&R is coordinated robotic manipulation. The operator gives the machine a general command to perform a task and the machine does as it is told without hands-on human control. A major accomplishment in that field has been the development of a robotic system that can, in the laboratory, coordinate the actions of two telerobotic arms to grasp and stabilize a tumbling satellite. The system has direct application, in the Space Station, for capturing and servicing satellites as they rendezvous with the station.

The year's major accomplishment was development of the hardware and software to grasp and stabilize a tumbling satellite. Though we are using commercial arm hardware, we are developing the computer hardware, software, and computer vision to accomplish the difficult task of coordinating the two arms. The system uses a five-camera video-sensor array and a special image processor to track a satellite that is spinning at 9.7 revolutions per minute. The equipment can do even better when the satellite is equipped with running lights.



The most challenging task in A&R is the autonomous movement of a remote vehicle through an unknown landscape. The vehicle senses its environment, plans its route to a goal, and performs a set of tasks along the way. Those tasks could include gathering samples, taking measurements, or taking pictures, always avoiding obstacles along the route. The vehicle must also be able to sense its own needs for maintenance and repair and to perform these tasks.

When we put an autonomous vehicle on the surface of Mars to conduct our scientific experiments there, we will not be able to drive it with human controllers on Earth. Commands take between 15 minutes and 1 hour to make the round-trip between Earth and Mars. So the rover must be intelligent enough to perform assigned tasks independently for at least as long as the round-trip signal time.

We have demonstrated both local and global route planning and remote driving with a six-wheeled vehicle that had been used for earlier research and demonstrations. The work was sponsored by the U.S. Army and NASA.

A core effort of supporting research and technology development underlies current demonstrations and will provide even more advanced technology for tomorrow's challenges. We are developing collaborative research efforts in space robotics with members of the Caltech faculty.

TECHNOLOGY SYSTEMS

Emergency Communication

Yet another communications advance saw JPL complete new work for the National Communications System, the federal agency that will be in charge of communications during national security or other emergency situations. In the event of a natural disaster or crisis, communication becomes a critical resource. But existing communications systems are likely to be severely disrupted.

JPL's task was to design a mobile communications satellite system to overcome loss of communications during a disaster. The work used as a scenario an 8.3-magnitude earthquake on the San Andreas fault in San Bernardino County.

Performance will be further tested with computer simulations during the coming year.

In another task, this one sponsored by the Department of Energy, JPL has continued to develop systems to measure the electric and magnetic environment around electric utility lines. Field meters were developed at JPL that measure both magnetic and electric fields of electric utility lines.

Electric Power Technology

The Laboratory and General Electric Corporation signed a contract in 1986 to design the SP-100 300-kilowatt electric space reactor power system.

A change in the required size, to 100 kilowatts, together with technical problems in the design, led to a redesign effort. GE made significant progress in developing many important components.

Another energy-related effort involves research into advanced electric power sources for spacecraft that are bound for the outer planets. We want to increase the efficiency of the nuclear power sources and their power-to-weight ratios by developing an Alkali Metal Thermoelectric Converter (AMTEC). AMTEC is an electrochemical heat engine whose working fluid is sodium. The system has a nuclear heat source that is coupled to the converter, which is then coupled to a radiator. Heat flows from the source, through the AMTEC, to the radiator. In the process, some of the heat is converted to electrical energy. The device's operation depends on a special ceramic material in the AMTEC that allows the sodium vapor to expand through the solid ceramic against an electric field, just as a gas expands against a piston in a conventional engine.

AMTEC has several potential advantages. It has no moving parts. Its power-to-weight ratio is three to five times higher than current nuclear power sources. And its efficiency is in the range of 20–25 percent.

Meanwhile, JPL's decade-long research into solar arrays continues to bear fruit. Based on experience gained from the Flat-Plate Solar Array Project, we continue to improve our understanding of the factors that determine the reliability of terrestrial photovoltaic power systems.

The work concentrates on understanding the physics of corrosion in solar cells. Research is sponsored by the Department of Energy through the Solar Energy Research Institute and Sandia National Laboratories.

In a final energy-research effort, scientists have used advanced spectroscopic techniques to advance our understanding of the chemical processes involved in making amorphous-silicon solar cells. The technique will lead to an improved-quality product.



The converted 70-meter antenna of the Madrid DSN Complex is at the top center of this photograph and the newest high-efficiency, 34-meter antenna is at the lower right.

TELECOMMUNICATIONS SYSTEMS

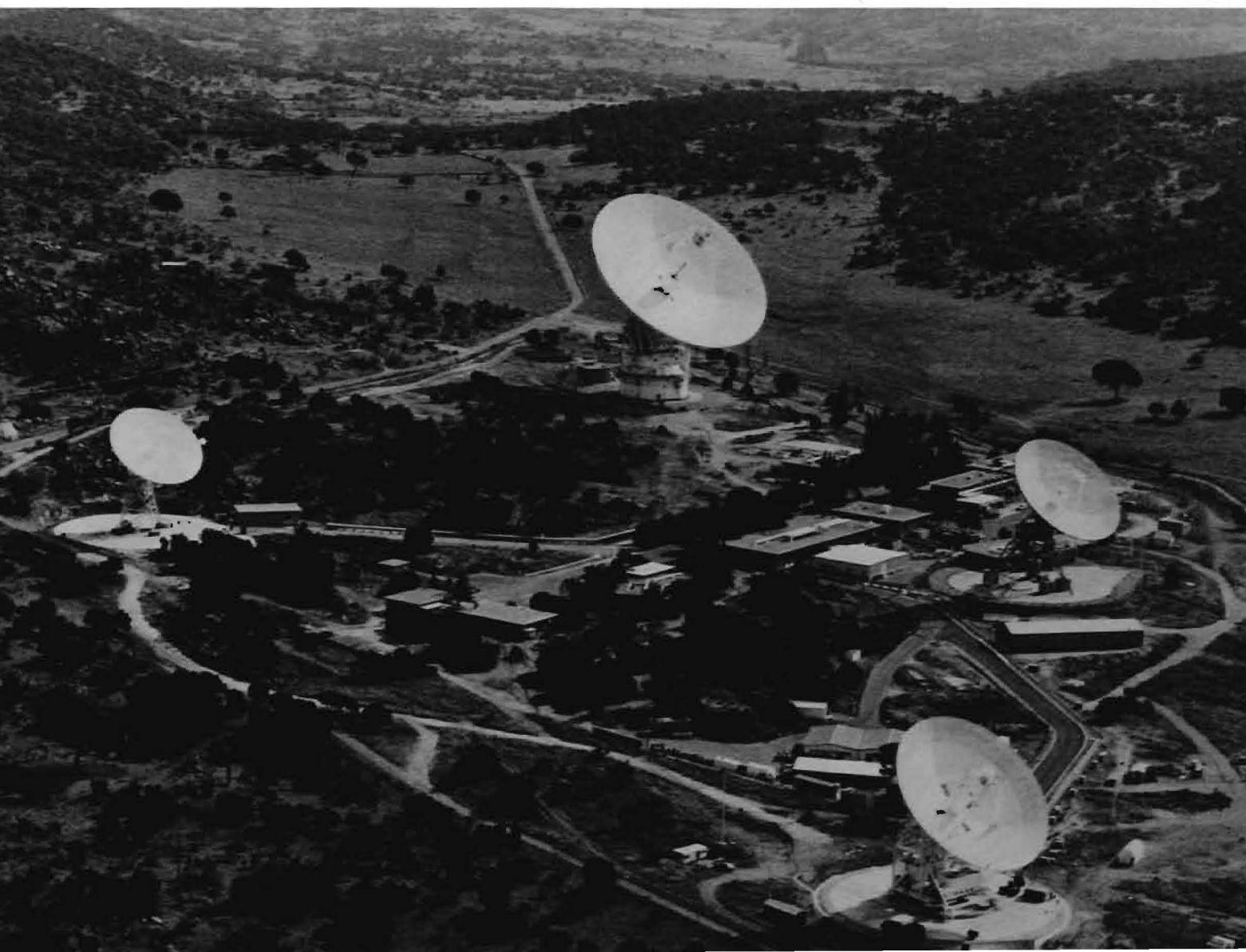
■ The Deep Space Network is NASA's worldwide system for transmitting instructions to spacecraft and receiving the data that they collect in deep space and Earth orbit. JPL manages the network.

The antennas are clustered at sites at Goldstone Dry Lake in California's Mojave Desert; near Madrid, Spain; and near Canberra, Australia. Those locations allow us to see spacecraft anywhere in the solar system. The Network Control Center and its supporting facilities are at JPL. Satellite and ground communications link all locations.

Each site is equipped with four large antennas from 26 to 70 meters in diameter. The

fourth antenna at Madrid, the last of the planned 34-meter, high-efficiency antennas, began service this year. During encounters all antennas at each complex can be arrayed to increase data return.

The antennas can also be teamed for scientific investigations, using techniques like very long baseline interferometry (VLBI), in which measurements made by two or more widely spaced antennas can be made to work like one giant antenna spanning the distance between them. The VLBI technique, originated by radio astronomers, is used both for navigating spacecraft and for precise geodetic measurements.





Communications Research

Our spacecraft are flying farther from Earth than ever before and the scientists who use them are demanding more and more data from them. Neptune is six times as far away as Jupiter. Therefore, the signal from a spacecraft at Neptune is only 1/36th as strong as at Jupiter.

To overcome that natural loss of signal strength and the ever-present sources of radio noise in the spacecraft, the receivers, and in space itself, we must devise clever ways to extract the ever-fainter signals from the noise.

For more than 30 years, JPL has been in the forefront of developing error-detecting and error-correcting codes for transmitting data. Data bits are transmitted by the spacecraft in specific patterns. The patterns often involve transmission of extra bits of data specifically for error correction. By analyzing the patterns of bits as groups of them are received on Earth, computers in the DSN and the Space Flight Operations Facility interpret the patterns, determine which bits have been degraded by noise and, from the context, can correct the offending bits to recover the original message.

Human beings do much the same thing quite well, without even thinking about it. For example, when we have a noisy telephone connection, we often make sense of the other person's words, just because we know what the person is talking about, and we can understand the message despite the telephone noise. That is error detection and correction.

Continuing that analogy, we do not want to ask the spacecraft to repeat its entire message, because the long travel time of the signals from spacecraft to Earth makes retransmission impractical. So we are seeking new methods to detect and correct errors.

Deep Space Network researchers searched through many potentially good error-correcting codes to find one that could be used on the Galileo spacecraft to increase its data return. The researchers found a code that

would increase the data return by around 50 percent and still be compatible with the existing Galileo data system.

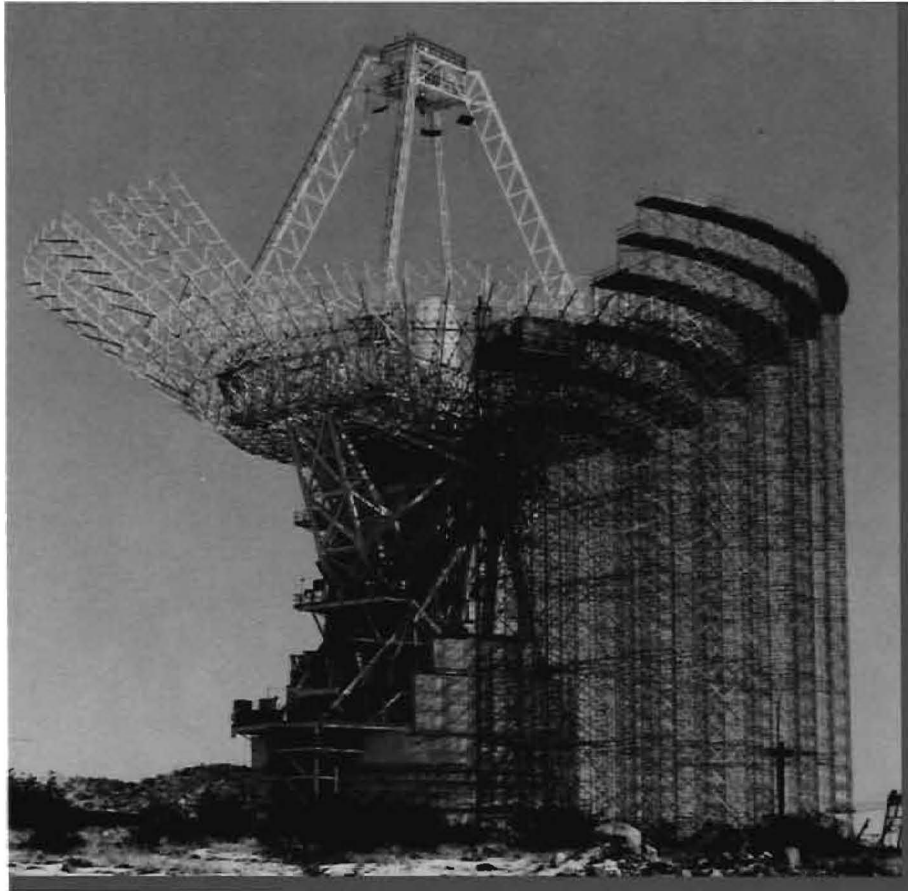
The improved code could provide much greater scientific return from the Galileo mission at the cost of a modest increase in computer complexity on Earth. Today's advanced very large scale integration technology can easily provide the increased decoding capability.

One advancement in communications technology will be of value in a broad range of terrestrial transportation needs. JPL and a group of collaborators conducted a series of tracking experiments to test the Global Positioning System (GPS), which uses NAVSTAR satellites. The researchers found an efficient way to use the system. By listening to signals from several NAVSTARs at the same time, the operator of an aircraft, a ship, or a ground antenna can determine his position relative to the spacecraft to within one meter. When all the GPS system is deployed, a navigator should be able to find his location within one-half meter.

The Deep Space Network uses antennas that are continents apart to precisely locate spacecraft. Very long baseline interferometry uses the relative positions of the antennas and the spacecraft to form a triangle, from which the spacecraft's location can be derived.

However, VLBI is a complicated process because the antennas are so far apart. In a new development, DSN radio experimenters were able to determine a spacecraft's location with high precision using antennas that are separated by only a few hundred kilometers.

To accomplish the feat requires close coordination of timing (within a few trillionths of a second) between the antenna stations. Using the technique with the antennas at Goldstone and the Owens Valley Radio Observatory, which are only 240 kilometers apart, we would be able to pinpoint Galileo's position to within 40 kilometers when it is at Jupiter, about 750 million kilometers from Earth.



The 64-meter antenna at Goldstone, California, is being upgraded to a 70-meter diameter.

Space Communications

Communication with distant spacecraft will always be its primary focus, but the DSN also supports Earth orbiters that are not compatible with NASA's new Tracking and Data Relay Satellite System. The DSN provides launch-to-transfer-orbit support to spacecraft bound for geosynchronous orbit, and emergency support for the tracking satellites themselves and for other spacecraft that would normally communicate through the relay satellite system.

During the year, the DSN continued to provide routine support to 17 spacecraft in deep space and in Earth orbit. The oldest, Pioneer 6, has survived for more than 22 years, returning solar weather data from its orbit around the Sun. The most distant spacecraft, Pioneer 10, followed, in order of distance, by Voyager 1, Pioneer 11, and Voyager 2, are returning scientific data from previously unexplored regions of the solar system. Besides

the two Voyagers, the DSN supported seven Pioneers, five Explorers, Nimbus-7, and Solar Max. The DSN also supported launch-to-orbit operations for GOES-H (United States), TV-SAT-1 (Germany), and ASTRO-C and ETS-V (Japan).

Work continued that will increase the DSN's capability to support Voyager 2's Neptune encounter in 1989 and the Galileo, Magellan, and Ulysses missions that begin in 1989 and 1990. During the Neptune encounter on August 24, 1989, Voyager 2's signals will be less than one-half as strong as at Uranus in 1986, because the distance from spacecraft to Earth has doubled. Yet scientific needs for data are undiminished. For the encounter, the DSN is upgrading its own antennas and preparing to array them with two other radio-astronomy antenna systems.

The Very Large Array of the National Radio Astronomy Observatory in Socorro, New Mexico, will be arrayed with the antennas at

Goldstone. Each of the twenty-seven 25-meter antennas at Socorro is being equipped to operate at X-band for the first time, to prepare for the Neptune encounter. By year's end, more than half of the antennas had been equipped. The new equipment will make the X-band frequency the most sensitive at the Very Large Array.

The combined signal from the Socorro antennas will be used with signals from the arrayed 70-meter and 34-meter antennas at Goldstone to provide a data rate more than double that which would have been available with Goldstone's antennas alone. The increase nearly compensates for the loss in power caused by the greater distance of Neptune, compared with Uranus. And the array of the Parkes Radio Telescope with the DSN antennas at Canberra, which was used for Voyager's Uranus flyby, will be used again for Neptune.

The 64-meter-diameter antennas of the DSN have provided primary support to planetary encounters since 1966. The antennas' performance is being improved. Their diameters are being increased to 70 meters and their efficiency is being improved through special shaping and improved surfaces on the reflectors. The upgrade at Madrid and Canberra was completed this year.

The upgrade of the 64-meter antenna at Goldstone began in October and will be complete in June 1988. The new 70-meter antenna will have the most accurate surface ever used on an antenna of its size. Average surface variation is only 0.5 millimeter.



APPLICATIONS PROJECTS

■ JPL projects that are sponsored by agencies other than NASA apply the Laboratory's special skills to solving problems that are of national interest. Late in the year, the NASA-sponsored technology development activities were moved under the Defense and Civil Programs Office and it was renamed the Technology and Applications Programs Office. The office is responsible for almost all of JPL's technology development activities.

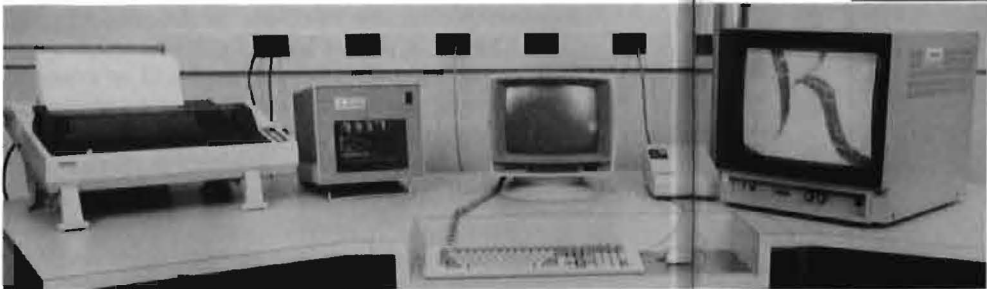
Applications projects address system developments and draw mostly on communications, information-management, and information-processing fields.

Charters of Freedom Monitoring System

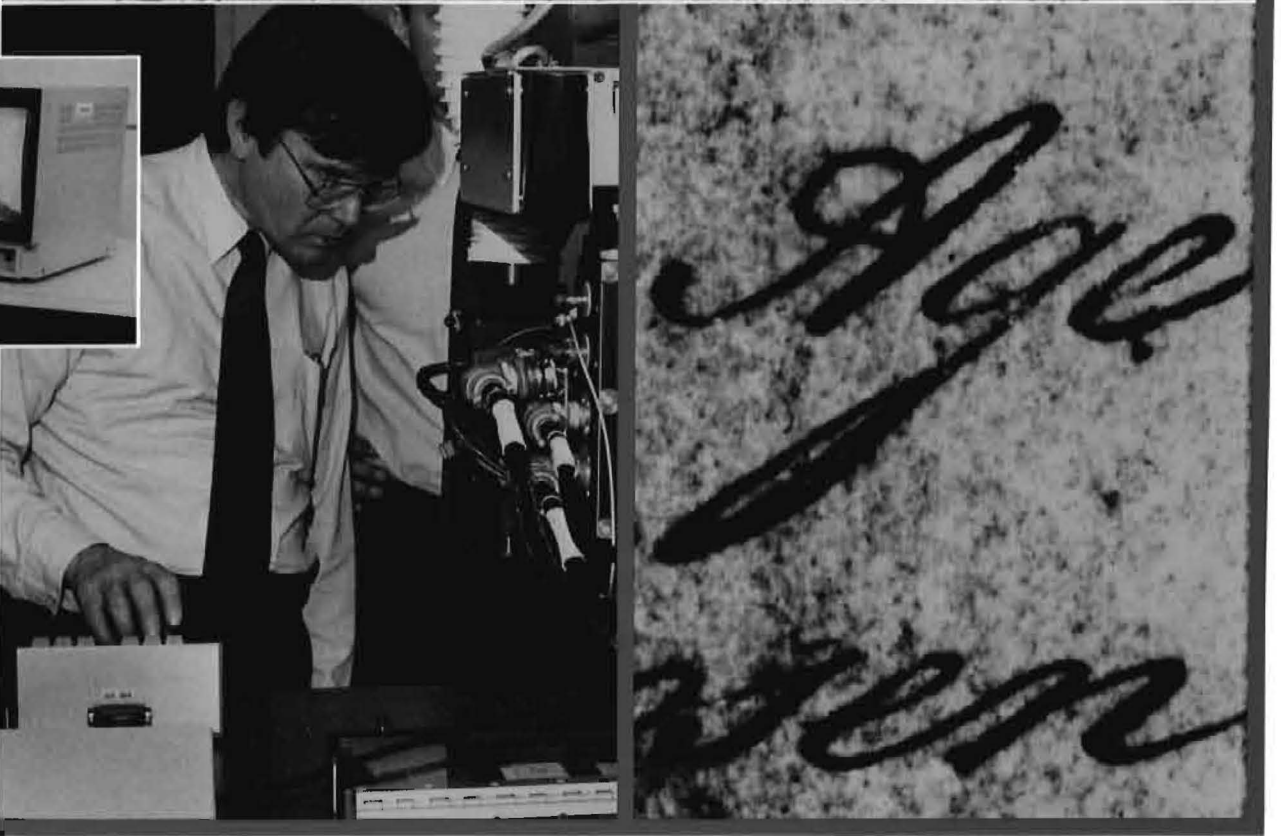
JPL developed and installed a document-monitoring system to track the condition of the United States Constitution, the Bill of

Rights, and the Declaration of Independence, in time for the U.S. Constitution's bicentennial. The documents are called the Charters of Freedom and are displayed at the National Archives in Washington, D.C.

The JPL system is designed to make a precise, microscopic, digital record of the original hand-inked documents to help with their preservation. The three have suffered some physical degradation over the two centuries of their existence. The system includes an imaging subsystem that is computer controlled and charge-coupled-device based and a stand-alone image processing system. The monitoring system was developed at JPL. The system was designed and built by Perkin Elmer Corporation.



A microscopic image of a few handwritten letters from the U.S. Constitution overlies a copy of the document. The enlargement of the Constitution was made with JPL's Charters of Freedom Monitoring System, which can find minute changes in the condition of the Charters of Freedom so that action can be taken to preserve them. The image-processing system's computer workstation and the CCD-based camera that were developed at JPL have been installed in the National Archives in Washington, D.C.



National Archives

ASAS/ENSCE Project

The All Source Analysis System/Enemy Situation Correlation Element (ASAS/ENSCE) mission is to field a baseline data-processing system for U.S. Army and Air Force tactical intelligence in the early 1990s.

ASAS/ENSCE uses computer workstations in mobile field modules. The computers receive large quantities of intelligence data, analyze and prioritize them, and then process the data for battlefield commanders.

JPL completed development of a versatile, portable computer workstation and demonstrated it at Fort Huachuca, Arizona, and in Washington, D.C. A rugged version of the workstation supported NATO's REFORGER exercise in Europe.

We continued development of a limited-capability configuration of the ASAS/ENSCE system for early use, and began to design and code the next major software releases.



Simulation of Area Weapons Effects

JPL is developing a comprehensive system that will safely simulate the effects of indirect-fire weapons during training exercises. Development of simulations of artillery or mortar fire and conventionally placed mines is nearly complete.

A launcher is in development and testing. It will propel a training projectile accurately at distances up to 1,200 meters. The launcher is automated so that crews can operate it safely with little training. Projectiles are detonated at about 28 meters in altitude. Detonation is controlled by self-contained custom-designed circuitry.

The Army wants to train its combat units under conditions that simulate real conflict. The noise of a projectile's explosion and an acoustic signal generated by a groove in the projectile's nose are processed by a lightweight device that computes and transmits a casualty-assessment signal similar to the effects of real combat. The device contains two microprocessors that are controlled by another JPL-designed VLSI microcircuit.

The system will be produced by industry and the designs will be transferred to the Army for acquisition.

Command and Control Automation

The Global Decision Support System, begun about two years ago, serves as the command and control system of the top three Military Airlift Command (MAC) echelons. Three releases of systems and applications software have been delivered to operations personnel. Using the Ada software language and methodology, the team has achieved productivity that is three times better than JPL and industry standards.

Analysis and Training Systems

We have been developing a computer-based system to provide large-scale land/air battle

simulation to help train high-level military commanders and their staffs. The project is called Joint Exercise Support System (JESS). It is a great improvement over previous training systems that used manual map boards and an elaborate rule book to specify results.

In previous years we delivered various versions of JESS to the United States Readiness Command. Shortly after the first operational version was completed, the Army adopted JESS as its standard corps and division staff training system. Corps Battle Simulation centers have been established at all five active-duty Army Corps, and JESS version 1.0 was installed in the centers as their primary training system.

The project is incorporating many improvements into a new version of the software, which is undergoing testing. Current JESS architecture will not allow some specific functional and operational improvements. Therefore, the team is developing a new design for JESS (version 2.0) that uses advanced computing hardware and architectural concepts.

Real-Time Weather Processor Project

The Laboratory has been working on a comprehensive weather-information system to support civil air traffic control for the Federal Aviation Administration (FAA). An important element of the system is the development of a next-generation weather radar system, and the project's major interface is with that system.

In July, the FAA decided to divide the weather processor development into two parts, to accelerate the delivery of meteorological processing equipment to Air Route Traffic Centers. JPL will continue to develop the radar weather-data processing system, while the FAA will acquire the other elements from commercial sources.

INSTITUTIONAL ACTIVITIES

■ Research and development costs for the fiscal year ending in September were \$892 million, a 9 percent increase over the previous year.

Costs for NASA-funded activities rose 13 percent to \$596 million. Defense and civil programs costs were \$290 million, an increase of 1 percent. The work force increased to 5,465 from 5,393 in 1986 and 5,247 in 1985.

Procurement obligations during fiscal year 1987 totaled \$613 million, 6 percent higher than in 1986. That included \$571 million to business firms, of which \$150 million went to small businesses and \$12 million to minority-owned businesses.

Progress continued on JPL's long-range plan to renew its facilities. Construction of the 38,000-square-foot Advanced Microdevices Laboratory began in January. Ground was broken in July for the Engineering Support Building, a 75,000-square-foot facility that will house 260 people and associated laboratories and a cafeteria.

In August a 115,000-square-foot facility in Reston, Virginia, was leased. It houses 400 JPL, NASA, and contractor personnel to support NASA's Space Station program.

Director's Discretionary Fund

The Director's Discretionary Fund (DDF) is the major resource to support innovative and seed efforts that cannot receive conventional task-order funding. The DDF has \$3 million a year.

This year the fund initiated 25 new research tasks, extended the objectives and awarded more funds to eight ongoing tasks, and provided modest assistance to several other support efforts. Proposals eligible for DDF funds cover a broad range of sciences and technologies. Areas of recent emphasis include advanced microelectronics, automation and robotics, infrared- and submillimeter-wavelength technology, and detection of planets beyond the solar system.

The DDF recognizes important mutual benefits from collaboration with faculty and students at Caltech and other universities, so cooperation is specifically encouraged. Eleven principal new and extended tasks funded this year involve university faculty collaborators.

President's Fund

The Caltech President's Fund provides a second, though smaller, source of discretionary funding. Currently at a level of \$1 million a year, the fund comes from Caltech and NASA resources on a dollar-for-dollar matching basis. The fund is administered by Caltech. An explicit objective of the President's Fund is to encourage interest and participation by university faculty and students in JPL research activities and to afford JPL staff members an opportunity for close association with research workers from the university community. The President's Fund provided resources for 14 new collaborative tasks this year.







NASA Honor Awards

The NASA Honor Awards program provides an annual opportunity for the agency and JPL to recognize outstanding individual and team efforts. NASA's selection process was rescheduled this year, so awards that would have been announced near the end of the year and could have been reported here will be delayed until early in 1988.

Patents and Technology Utilization

During the year, the Office of Patents and Technology Utilization reported 241 inventions and technical innovations from JPL work. The office also answered 29,981 requests from industry and the public for technical information on JPL inventions and innovations selected by NASA and published in the NASA periodical *Tech Briefs*. The U.S. Patent Office issued 37 patents to Caltech and NASA on inventions made at JPL.

NASA conferred the following awards on JPL inventors and innovators:

- \$12,000 for "Portable Reflectance Spectrometer," awarded as follows: \$9,000 to Alexander F.H. Goetz, \$1,500 to Richard A. Graham, and \$1,500 to Tetsuo Ozawa.

- \$3,000 to Gary C. Bailey for "Integrating IR Detector Imaging System."

- \$2,000 to Vance Tyree and Chialin Wu (shared equally) for "Real-Time Multiple-Look Synthetic Aperture Radar Processor for Spacecraft Applications."

- \$1,000 to Bruce L. Gary for "System for Indicating Fuel-Efficient Aircraft Altitude."

Another 260 JPL employees received minimum (\$250–\$500), and nominal (\$501–\$999) patent awards, and *Tech Brief* (\$150) awards to total \$48,700.

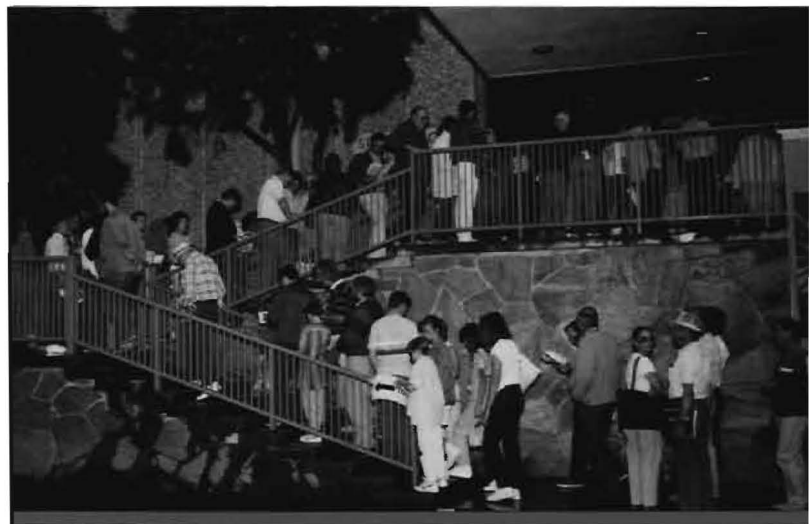


A Tradition of Discovery

"A Tradition of Discovery," the first major open house held at JPL in six years, turned out to be one of the year's true highlights.

The open house took place over two weekends in June. Despite rain and heavy clouds, the first weekend saw thousands of excited visitors pour through the gates to the Laboratory. By the second week's end, more than 48,000 people had witnessed the work we do here.

Tours and demonstrations throughout the Laboratory allowed our visitors to see how we accomplish such a variety of scientific and engineering advancements and to learn the many uses of our scientific research.



Distinguished Visiting Scientist Program

The Distinguished Visiting Scientist Program was established at JPL to promote an interchange between researchers worldwide and our own JPL and Caltech scientists and engineers. The intent of the program is to strengthen and advance areas of research that are of particular interest to JPL, by providing a forum for the exchange of ideas, research methods, and technical expertise.

The following renowned scientists have spent from two to twelve months at JPL, offering us their insights and expertise in the indicated field.

Thorwald G. Andersson Chalmers University of Technology, Sweden	Molecular beam epitaxy
Arthur L. Bloom Cornell University, New York	Radar remote sensing
William B. Bull University of Arizona, Arizona	Tectonic/climate geomorphological models
C. Thomas Elliott Royal Signals and Radar Establishment, United Kingdom	Optoelectronics
Robert C. Jaklevic Ford Scientific Laboratory, Michigan	Scanning tunneling microscopy
John H. Manley Computing Technology Transition, Inc., Pennsylvania	Information systems software engineering
Hadis Morkoc University of Illinois, Illinois	Advanced microelectronics
Albert Overhauser Purdue University, Indiana	Solid-state physics
Max E. Schulz University of Erlangen, Federal Republic of Germany	Space microelectronics

Senior Research Scientists and Engineers

The position of senior research scientist or engineer is a special recognition of outstanding individual achievement. Appointees are leaders in their fields, recommended to the position by peer review.

The outstanding researchers listed below are active participants in programs key to the research and institutional goals of JPL who earned their research appointments this year.

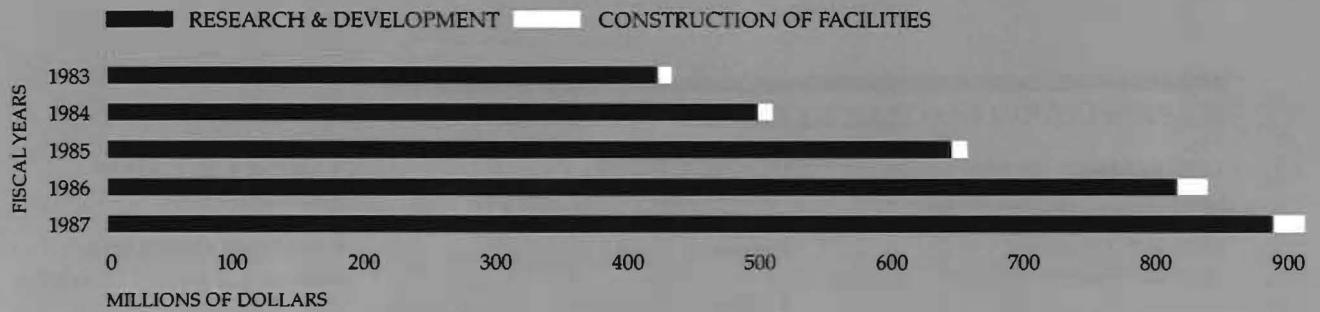
Senior Research Scientists

Arvydas J. Kliore	Spacecraft radio science
Gunnar F. Lindal	Spacecraft radio science
Richard T. Woo	Radio science/radio scintillations

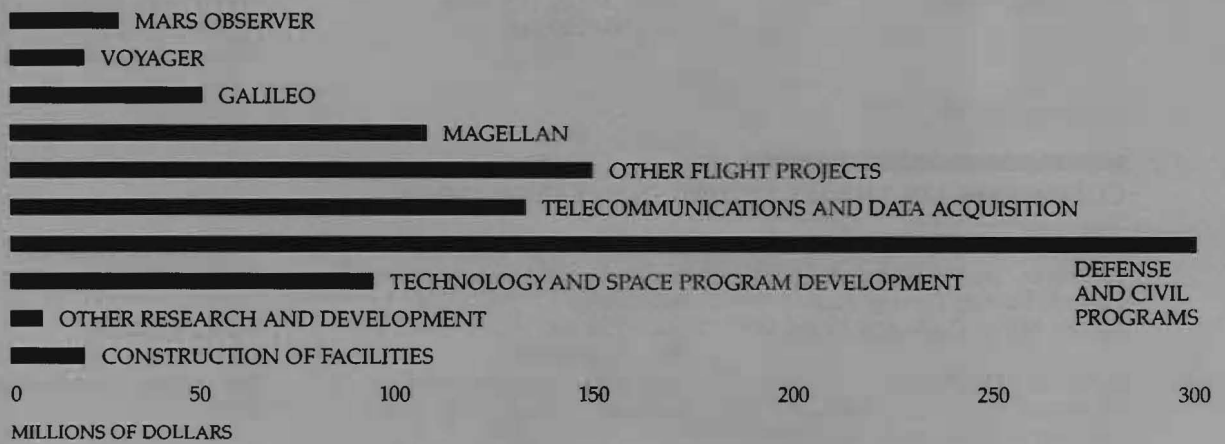
Senior Research Engineers

Hua-Kuang Liu	Optical processing and holography
William J. Wilson	Microwave/millimeter- wave systems

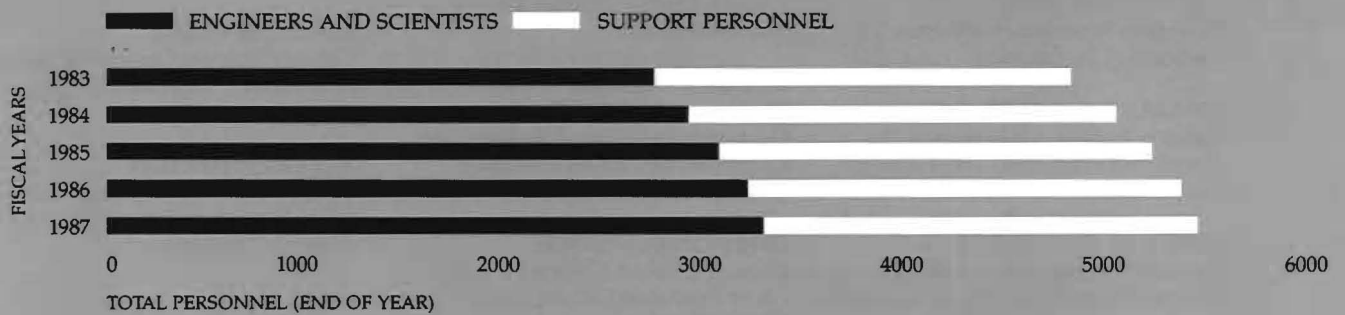
TOTAL COSTS



FISCAL 1987 COSTS



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